EXPERT REPORT
OF
MARK JACOBSON, Ph.D.

Professor, Dept. of Civil and Environmental Engineering
Director, Atmosphere/Energy Program
Senior Fellow, Woods Institute for the Environment
Senior Fellow, Precourt Institute for Energy
Stanford University

Kelsey Cascadia Rose Juliana; Xiuhtezcatl Tonatiuh M.,
through his Guardian Tamara Roske-Martinez; et al.,
Plaintiffs,

v.

The United States of America; Donald Trump,
in his official capacity as President of the United States; et al.,
Defendants.

IN THE UNITED STATES DISTRICT COURT
DISTRICT OF OREGON

(Case No.: 6:15-cv-01517-TC)

Prepared for Plaintiffs and Attorneys for Plaintiffs:

Julia A. Olson
JuliaAOlson@gmail.com
Wild Earth Advocates
1216 Lincoln Street
Eugene, OR 97401
Tel: (415) 786-4825

Philip L. Gregory
pgregory@gregorylawgroup.com
Gregory Law Group
1250 Godetia Drive
Redwood City, CA 94062
Tel: (650) 278-2957

TABLE OF CONTENTS

TABLE OF ACRONYMS AND ABBREVIATIONS

BAU:	business as usual
CCS:	carbon capture and sequestration
coal-CCS:	coal with carbon capture and sequestration
CO_2:	carbon dioxide
CSP:	concentrated solar power
DOE:	United States Department of Energy
EIA:	United States Energy Information Administration
EPA:	United States Environmental Protection Agency
HVAC:	heating, ventilation and air conditioning
HVDC:	high-voltage direct-current
IPCC:	United Nations Intergovernmental Panel on Climate Change
kW:	kilowatt (measure of electric power)
kWh:	kilowatt hour
MW:	megawatt (measure of electric power)
OTA:	United States Congress, Office of Technology Assessment
ppm:	parts per million
ppmv:	parts per million by volume
PV:	photovoltaic
R&D:	research and development
RE:	renewable energy
UNFCCC:	United Nations Framework Convention on Climate Change
WWS:	wind, water, and sunlight

INTRODUCTION

I, Mark Jacobson, have been retained by Plaintiffs in the above-captioned matter to provide expert testimony about the feasibility of transitioning the United States of America to 100% clean and renewable energy in all energy sectors by mid-century, including whether this transition would remedy the constitutional violations alleged in the First Amended Complaint in this case. All energy sectors include electricity, transportation, heating/cooling, and industry.

QUALIFICATIONS

Since 1989, I have been researching academically and professionally, the impacts of human emissions of gases (including carbon dioxide and other greenhouse gases) and particles (including black carbon) on air pollution, human health, weather, and climate. Starting in 1999, I began examining in detail clean, renewable energy solutions to these problems. In 2015, this research culminated in the development of roadmaps to transition the all-sector energy infrastructures of each of the 50 United States to 100% clean, renewable energy by 2050 (Jacobson et al., 2015a, which includes a link to the spreadsheets used to derive all numbers in the paper). The research has also resulted in the development of 100% clean, renewable energy roadmaps for 139 countries of the world (Jacobson et al., 2017a, which also includes a link to spreadsheets) and electric power grid stability analyses for the 48 contiguous United States (Jacobson et al., 2015b) and for 20 world regions containing the 139 countries examined (Jacobson et al., 2018) after those states and countries have converted to 100% clean, renewable energy. I carried out this research, analysis, and clean, renewable energy roadmap development primarily with Dr. Mark Delucchi at U.C. Berkeley, but also along with several other experts. The purpose of this report is to summarize the portion of this research related to the United States and its major conclusions and implications on the feasibility of transitioning the country swiftly off of fossil fuels to clean and renewable energy in all sectors by mid-century.

The opinions expressed in this report are my own and are based on the data and facts available to me at the time of writing. All opinions expressed herein are to a reasonable degree of scientific certainty, unless otherwise specifically stated. Should additional relevant or pertinent information become available, I reserve the right to supplement the discussion and findings in this expert report in this action.

My full CV, including a list of publications I authored within the last ten years, is attached as **Exhibit A** to my report. My report contains a list of citations to the principal documents that I have used or considered in forming my opinions, listed in **Exhibit B**. **Exhibit C** contains a summary of my previous expert testimony. **Exhibit D** is a chart summarizing other decarbonization studies of which I am aware. I also attach, as **Exhibits E-H**, my central papers discussed herein.

In preparing my expert report and testifying at trial, I am deferring my expert witness fees to the charged plaintiffs given the financial circumstances of these young plaintiffs. If a party seeks discovery under Federal Rule 26(b), I will charge my reasonable fee of $200 per hour for the time spent in addressing that party's discovery.

EXECUTIVE SUMMARY

In this report, I summarize research, conclusions, and implications of studies that I and my colleagues previously performed to develop 100% clean, renewable all-sector (electricity, transportation, heating/cooling, industry) roadmaps (plans) for the 50 United States (Jacobson et al., 2015a) and to analyze resulting electric grid stability for the 48 contiguous United States (Jacobson et al., 2015b). I also rely on our updated peer-reviewed research on an energy roadmap for the United States as a whole (Jacobson et al., 2017a) and a grid stability study for the United States plus Canada combined (Jacobson et al., 2018). I set forth a substantive discussion of numbers from the 50-state roadmaps in Jacobson et al. (2015a) where the numbers are set forth both on a state specific basis and for the U.S. as a whole. However, the U.S.–as-a-whole numbers were updated in Jacobson et al. (2017a) based on updated cost, efficiencies, and other data. Jacobson et al. (2017a) does not have an in-depth discussion of those data simply because the 2015a study provides state-by-state breakdowns as well. Nevertheless, both studies provide a consistent conclusion. Namely, I conclude in both studies that it is both technically and economically feasible to transition from a predominantly fossil fuel-based energy system to a 100% clean, renewable energy system for all energy sectors by 2050, with about 80% conversion by 2030, even after taking into account the U.S. Department of Energy's (DOE's) Energy Information Administration's (EIA's) energy demand forecasting and taking into account efficiencies resulting from the transition from fossil fuels to clean, renewable energy.

Presently, fossil fuels supply more than 80% of our all-purpose energy in the United States, not out of necessity, but because of political preference and historic government support that led to the development and maintenance of a widespread fossil-fuel infrastructure. Our plans provide state-by-state roadmaps to replace 80% of existing fossil fuel energy by 2030 and 100% by 2050. The main concept is to electrify all energy sectors with existing or near-existing technologies, and then to generate the electricity for all sectors with 100% wind, water, and sunlight (WWS), namely onshore wind, offshore wind, utility-scale photovoltaics (PV), rooftop PV, concentrated solar power (CSP) with storage, geothermal power, wave power, tidal power, and hydroelectric power. A 100% WWS system would also require electricity storage, heat storage, cold storage, and some hydrogen storage along with an expanded transmission and distribution system.

First, based on our 2015 study (Jacobson et al., 2015a), converting to 100% WWS would reduce the U.S.-average end-use power demand by a mean of ~39.3%. Approximately 82.4% of the reduced power demand is due to a) the higher work output to energy input of electricity compared with fossil-fuels (burning fossil fuels to move vehicles results in much more waste heat than using electricity), and b) eliminating the energy needed to mine, transport, and refine fossil fuels and uranium (because wind and solar energy, for example, come right to the wind turbine or solar panel, respectively). The rest of the reduction in power demand is due to end-use energy efficiency and conservation improvements beyond those expected in a business-as-usual (BAU) case.

Second, averaged over the United States, our roadmaps propose that all-purpose U.S. energy in 2050 could be met with ~30.9% onshore wind, ~19.1% offshore wind, ~30.7% utility-scale photovoltaics (PV), ~7.2% rooftop PV, ~7.3% concentrated solar power (CSP) with storage, ~1.25% geothermal power, ~0.37% wave power, ~0.14% tidal power, and ~3.01% hydroelectric

power (where virtually all hydroelectric dams exist already). This is only one of many possible mixes. We have run our model with other mixes as well to demonstrate that a 100% WWS system by 2050 is feasible (e.g., Jacobson et al., 2017a).

Third, over all 50 states, converting from fossil fuel energy to WWS would provide an estimated 3.9 million 40-year full-time construction jobs and about 2.0 million 40-year full-time operation jobs for the energy facilities alone.

Fourth, converting from fossil fuel energy to WWS would also eliminate ~62,000 (19,000-115,000) U.S. air pollution premature mortalities per year today and ~46,000 (12,000-104,000) per year in 2050, avoiding ~$600 ($85-$2,400) billion per year (2013 dollars) in 2050, based on statistical cost of life as defined by the U.S. government, equivalent to ~3.6 (0.5-14.3) percent of the 2014 U.S. gross domestic product.

Fifth, converting from fossil fuel energy to 100% WWS would further eliminate ~$3.3 (1.9-7.1) trillion per year in 2050 global warming costs to the world due to U.S. emissions.

Sixth, these plans will result in each person in the U.S. in 2050 saving ~$260 (190-320) per year in energy costs ($2013 dollars) and U.S. health and global climate costs per person decreasing by ~$1,500 (210-6,000) per year and ~$8,300 (4,700-17,600) per year, respectively.

Seventh, the new footprint over land required to implement our plan would be ~0.42% of U.S. land. The spacing area between wind turbines, which can be used for multiple purposes, will be ~1.6% of U.S. land area. 0.42% of U.S. land is equivalent to ~14,800 square miles. For comparison, an upper bound of ~75,000 square miles of land (2.1% of U.S. land area) may have been used to date for roads, well pads, and storage facilities for the 2.5 million inactive and 1.7 million active oil and gas wells alone in the United States to date (Fracktracker Alliance, 2015). Pennsylvania alone has ~560,000 abandoned oil and gas wells (Pennsylvania Department of Environmental Protection, 2016). 20,000 new oil and gas wells are drilled in the United States every year. Allred et al. (2015) estimate that the area taken up by well pads, roads, and storage facilities for natural gas wells sum to 0.0178 square mile per well. Extrapolating this estimate to oil wells and to all abandoned plus active oil and gas wells in the U.S. gives the 75,000 mi^2 estimate. While this is an upper bound for oil and gas wells, coal and oil extraction has required additional land as have oil and gas pipelines, oil refineries, gas stations, power plants, and other oil, gas, and coal infrastructure, which will become obsolete upon the transition to 100% clean and renewable energy.

Eighth, the state-by-state roadmaps have been calculated to keep the 48 contiguous state U.S. grid stable at low cost in two separate peer-reviewed studies under multiple storage scenarios (Jacobson et al., 2015b; Jacobson et al., 2018). In the latter study, grid stability over the U.S. and Canada combined were found under three different scenarios, including two with no added hydropower turbines and one with added hydropower turbines.

In other words, the roadmaps will keep the lights on. Power supply will continue to match demand as it currently does, every minute of every day. Although the wind doesn't always blow and the sun doesn't always shine, it is possible to match power demand during those periods at a given

location by using stored energy, shifting the time of peak demand for energy with financial incentives (demand response), and by adding some long-distance transmission to connect wind and solar in remote locations to cities. In our studies, storage is in the form of heat (in water, rocks, and thermal mass); cold (in ice and water); electricity (in concentrated solar power (CSP) with storage, batteries, pumped hydropower systems, and existing hydropower dams); and hydrogen (for use in transportation). In our studies, we have found that the grid can stay stable with no coal, natural gas, oil, biofuels, or nuclear power. The resulting 2050-2055 U.S. electricity social cost (energy cost plus health cost plus climate cost) for a full system is much less than for current energy sources, and the energy cost alone is similar or less.

In sum, conversions of the energy infrastructure of the United States to 100% wind, water, and sunlight for all purposes is technically and economically feasible at low cost and high benefit. Based upon my review of the available information and pertinent literature identified herein, as well as my many years of experience as described herein, I conclude that a transition to 100% clean, renewable energy by mid-century would stop the affirmative government infringement of the youths' constitutional rights as described in the First Amended Complaint, and even though not all of the harm caused by historic emissions would be remediated, it would put the nation on the correct path toward climate stabilization.

EXPERT OPINION

1. Technological and Economic Feasibility of Converting 100% of Our Energy From Fossil Fuels to Clean, Renewable Energy For All Sectors by 2050 and 80% by 2030.

Our research suggests that it is technologically and economically possible to electrify fully the energy infrastructures of all 50 United States and provide that electricity with 100% clean, renewable wind, water, and sunlight (WWS) at low cost, if the transition is commenced immediately (Jacobson et al., 2015a; 2017a). Whereas, a 100% transformation is technically and economically possible by 2030, we believe that, for social and political reasons, a more practical expectation to transition all sectors (electricity, transportation, heating/cooling, industry) is 80% by 2030 and 100% by 2050. These conclusions are based upon the assumption that the transition commences immediately. Our research further finds that the U.S. electric power grid with 100% WWS can stay stable at low cost (similar or less than today's direct energy cost and much less than today's social cost, which includes energy, health, and climate costs) because electrifying transportation and heating creates more flexible loads, allowing grid operators to shift times of peak demand more readily (Jacobson et al., 2015b; 2018). Further, flexible loads allow low-cost storage options for heat and cold to be used to displace electricity demand and store excess electricity rather than wasting it.

The methodology for this research, outlined in detail in Jacobson et al. (2015a,b) and updated in Jacobson et al. (2017a; 2018), is as follows:

1) For each of the 50 states, we start with contemporary business-as-usual (BAU) end-use power demand by fuel type in the residential, commercial, transportation, and industrial sectors.

2) We use U.S. Department of Energy (DOE) Energy Information Administration (EIA) data and other data to project BAU end-use power demand by fuel type to 2050.
3) We electrify end-use demand in 2050 by fuel type in each sector, for each state. For some sectors, electricity is used to produce hydrogen.
4) We specify a mix of WWS electric power generators to meet the end-use electric demand in each state. The mix is limited and optimized by the technical potentials of each WWS resource in each state.
5) We calculate the required footprint and spacing area required for the WWS technologies.
6) We calculate the cost of constructing the WWS infrastructure for each state, including necessary upgrades to national electricity transmission infrastructure.
7) We calculate the number of long-term, full-time construction and operation jobs required for the generators and the corresponding number of jobs lost in the BAU energy sectors, primarily in the fossil fuel industry.
8) We calculate the air pollution mortality and morbidity reduction and corresponding health cost reduction due to transitioning from BAU to WWS.
9) We calculate the greenhouse gas emission reduction and corresponding climate cost reduction due to transitioning from BAU to WWS.
10) We use a weather prediction model to predict the time-dependent wind and solar fields in 2050 in each of the 48 contiguous U.S. states under the 100% WWS case in each state.
11) We project time-dependent power demand to 2050 from contemporary data.
12) We simulate the time dependent matching of power demand with WWS supply over the U.S. every 30 seconds for 6 years, with zero loss of load, accounting for low-cost heat storage (in water and rocks), cold storage (in water and ice), electricity storage (in concentrated solar power with storage, pumped hydroelectric storage, batteries, and hydroelectric power), demand response, and long-distance transmission.
13) We calculate the resulting cost of energy matching supply with demand.

The research concludes that converting from fossil fuel combustion to a completely electrified system for all purposes could reduce U.S.-averaged end-use power demand (load) ~39.3%. Approximately 82.4% of the reduced electricity use results from the higher work output to energy input of electricity over fossil fuels and the elimination of energy needed to mine, transport, and refine fossil fuels and uranium. The rest of the reduced electricity use is due to end-use energy efficiency and conservation improvements beyond those expected in a business-as-usual (BAU) case. The conversion to WWS should also stabilize energy prices since fuel input costs will be zero, avoiding much of the market fluctuations in the price of oil, coal, and gas.

Remaining all-purpose annually-averaged end-use U.S. load, based on the Jacobson et al. (2015a) study, is proposed to be met (based on 2050 energy estimates) with ~328,000 new onshore 5-MW wind turbines (providing 30.9% of U.S. energy for all purposes), ~156,000 off-shore 5-MW wind turbines (19.1%), ~46,500 50-MW new utility-scale solar-PV power plants (30.7%), ~2,270 100-MW utility-scale CSP power plants (7.3%), ~75.2 million 5-kW residential rooftop PV systems (3.98%), ~2.75 million 100-kW commercial/government rooftop systems (3.2%), ~208 100-MW geothermal plants (1.23%), ~36,000 0.75-MW wave devices (0.37%),

~8,800 1-MW tidal turbines (0.14%), and no new hydroelectric plants in the 48 contiguous states but 3 new hydroelectric plants in Alaska. The output of existing hydroelectric plants would be increased slightly so that hydropower supplies 3.01% of U.S. all-purpose power.

The Jacobson et al. (2015b) grid integration study based on the 50-state plans suggests that an additional ~1,360 CSP plants (providing an additional ~4.38% of annually-averaged load) and 9,380 50-MW solar-thermal collection systems for heat storage in soil (providing an additional 7.21% of annually-averaged load) would be needed as a first estimate to ensure a reliable grid. That study also assumed an increase in the peak hydropower discharge rate while holding the annual-average hydropower output constant. It also assumed a significant amount of underground thermal energy storage. This was just one possible mix of energy generators and storage. While that study faced criticism from authors, the criticisms were not only responded to point-by-point (Jacobson et al., 2016; 2017b) but the most significant ones were also shown to be moot in a follow-up peer-reviewed published study (Jacobson et al., 2018).

The subsequent study (Jacobson et al., 2018) performed a similar calculation as in Jacobson et al. (2015b) but with more storage options, including two with zero added hydropower turbines and one with zero underground or other thermal energy storage. More specifically, the additional simulations included (1) zero increase in the hydropower discharge rate but increasing the discharge rate of concentrated solar power (CSP) and adding battery storage while keeping thermal energy storage; and (2) zero increase in the hydropower discharge rate and zero thermal energy storage but using CSP with storage, batteries, and heat pumps instead.

Simulations for Jacobson et al. (2018) were performed for 20 world regions, including the United States plus Canada, island countries, medium-sized countries, and large countries and continents, rather than just one world region in Jacobson et al. (2015b). All simulations for all world regions resulted in stable grids at low cost over a 5-year simulation period, including with no added hydropower turbines and, in one case, with no thermal energy storage at all. These results for extreme conditions suggest there are multiple intermediate solutions with a variety of combinations of WWS storage technologies and resources. All methods resulted in low-cost solutions and 100% WWS by 2050. The fact that the system works with either increased hydropower discharge or increased CSP and batteries or CSP, batteries, and heat pumps is illustrative of the feasibility of transitioning the nation's energy system to 100% WWS. There is not just one way of achieving the transition, but many pathways. In fact, even critics of our methodology do not disagree with the conclusions we reach.[1]

Practical implementation considerations will determine the actual design and operation of the U.S. energy system and may result in technology mixes different than proposed here (e.g., more rooftop PV, less power plant PV).

Other studies in the U.S. and abroad provide parallel support for the ability to swiftly move away from fossil fuels. These studies are briefly summarized in **Exhibit D**. While I do not endorse

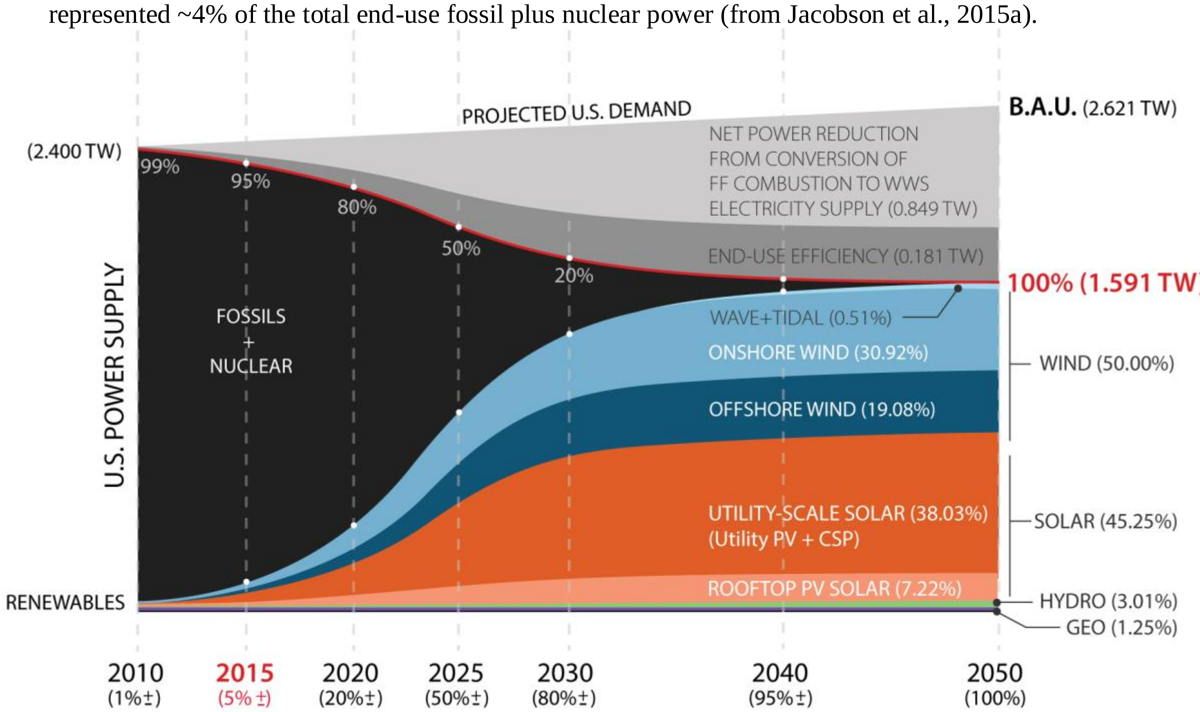
---

[1] June 20, 2017 Daniel Kammen Twitter: "A significant misunderstanding here: yes the 100% target is needed AND is feasible, but one must do the analytics correctly to be useful."

each of these studies and not all of the studies consider all energy sectors or 100% clean energy by 2050 as we do, collectively they illustrate the vast potential and feasibility of swift decarbonization and transition to clean, renewable energy. Specifically, several of these published studies conclude that 100% renewable energy for all sectors by 2050 for France, the European Union, and globally is feasible.

The timeline for conversion under either modeled scenario is proposed as follows: 80% of all energy to be WWS by 2030 and 100% by 2050 (**Figure 1**). If this timeline is followed, implementation of these plans and similar ones for other countries worldwide provides the pathway to eliminate energy-related global warming; air, soil, and water pollution; and energy insecurity. Transitioning at this pace should avoid global temperatures from rising more than 1.5°C as a peak temperature increase since 1870 and reduce CO_2 back to 350 ppm by 2100 (Section 2). Transitioning to 100% WWS by 2050 also provides the best opportunity for the federal government to further reduce global surface and ocean temperatures to levels that will over the long term stabilize the planet's ice sheets.

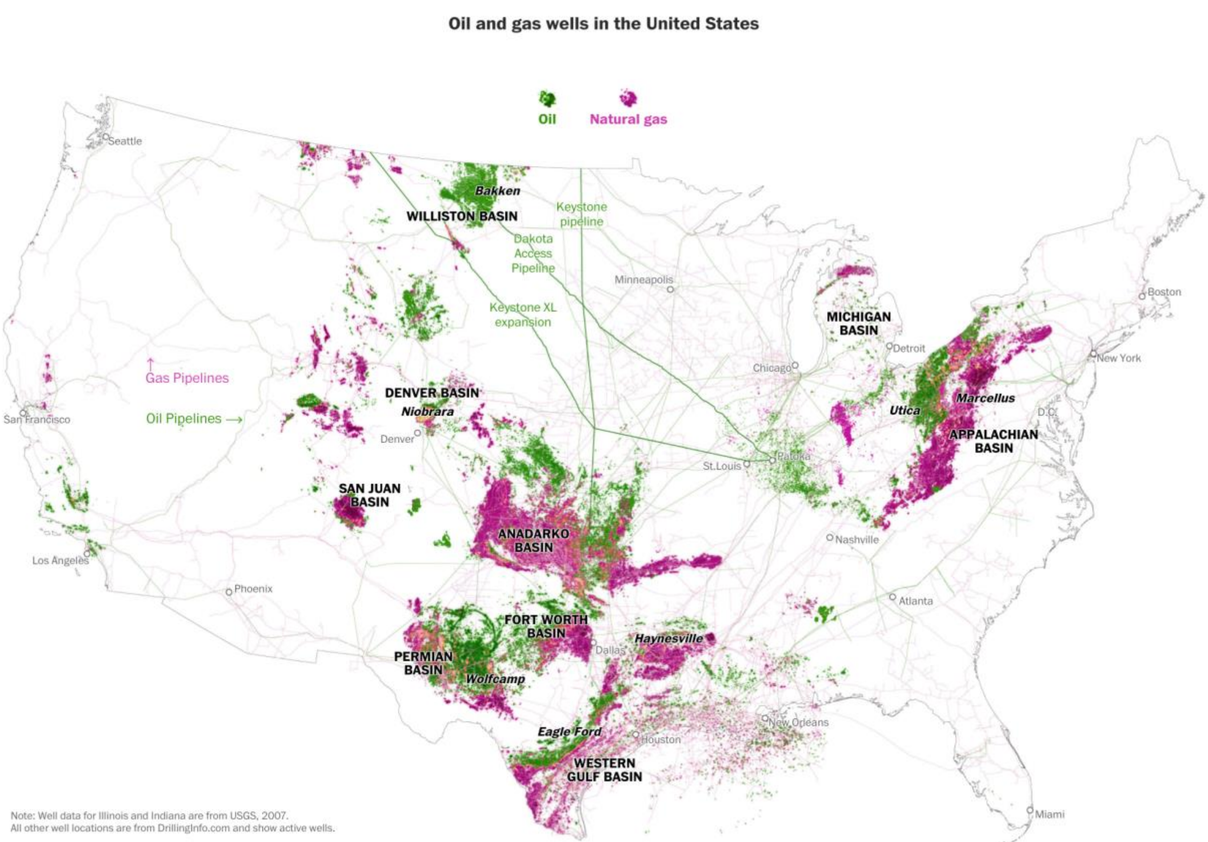
Figure 1. Time-dependent change in U.S. end-use power demand for all purposes (electricity, transportation, heating/cooling, and industry) and its supply by conventional fuels and WWS generators based on the state roadmaps proposed. Total power demand decreases upon conversion to WWS due to the higher work output per unit energy input of electricity over combustion, the elimination of energy used to mine, transport, and refine fossil fuels, and additional end-use energy efficiency measures in the WWS case. The percentages on the horizontal date axis are the percent conversion to WWS that has occurred by that year. The percentages next to each WWS source are the final estimated penetration of the source. The 100% demarcation in 2050 indicates that 100% of all-purpose power is provided by WWS technologies by 2050, and the power demand by that time has decreased. In 2010 nuclear power represented ~4% of the total end-use fossil plus nuclear power (from Jacobson et al., 2015a).



The additional footprint on land for WWS devices is equivalent to about 0.42% of the U.S. land area, mostly for utility scale PV. An additional on-land spacing area of about 1.6% is required for onshore wind, but this area can be used for multiple purposes, such as open space, agricultural land, or grazing land. The land footprint and spacing areas (open space between devices) in the proposed scenario can be reduced by shifting more land based WWS generators to the ocean, lakes, and rooftops.

As described previously, 0.42% of U.S. land is equivalent to ~14,800 square miles. For comparison, an upper bound of ~75,000 square miles of land (2.1% of U.S. land area) may have been used to date for roads, well pads, and storage facilities for the 4.2 active plus inactive oil and gas wells in the United States (Fracktracker Alliance, 2015). Additional land is required for coal and oil extraction, oil and gas pipelines, oil refineries, gas stations, power plants, and other oil, gas, and coal infrastructure (see **Figure 2**). Thus, the roadmaps here will take much less footprint than oil and gas alone in the United States.

Figure 2. Oil and Gas Wells in the United States (Meko and Karklis, Wash. Post, 2017).



Offshore oil and gas infrastructure is similarly extensive for the Gulf of Mexico, as depicted in **Figure 3**.

Figure 3. Gulf Coast Oil and Gas Infrastructure (Meko and Karklis, Wash. Post, 2017).

The 2017 unsubsidized business costs of new onshore wind and utility-scale solar plants is already less than that of new natural gas power plants (Lazard, 2017). Rooftop PV, offshore wind, tidal, and wave are more expensive, but their costs are declining rapidly. By 2030 and

2050, however, the business costs of all WWS technologies are expected to drop, whereas conventional fuel costs are expected to rise (Jacobson et al., 2015a and references therein).

In 2050, the direct (business) cost of a full 100% WWS grid-integrated system (including generation, transmission, distribution, and storage) is calculated to be similar or less than that of a fossil fuel system (Jacobson et al., 2015b; 2018). The total social cost (business cost plus health and climate cost) of a 100% WWS system will be about one-third to one-fourth that of a fossil-fuel system due to the high climate and health costs of fossil fuels (Jacobson et al., 2015b; 2018).

The 50-state WWS roadmaps are anticipated to create ~3.9 million 40-year construction jobs and ~2.0 million 40-year operation jobs for the energy facilities alone, outweighing the ~3.9 million jobs lost to give a net gain of 2.0 million 40-year jobs. Earnings during the 40-year construction period for these facilities (in the form of wages, local revenue, and local supply-chain impacts) are estimated to be ~$223 billion per year in 2013 dollars and annual earnings during operation of the WWS facilities are estimated at ~$132 billion per year. Net earnings from construction plus operation minus lost earnings from lost jobs are estimated at ~$85 billion per year.

The state roadmaps will reduce U.S. air pollution mortality by ~62,000 (19,000-115,000) U.S. air pollution premature mortalities per year today and ~46,000 (12,000-104,000) per year in 2050, avoiding ~$600 (85-2,400) billion per year (2013 dollars) in 2050, equivalent to ~3.6% (0.5-14.3) of the 2014 U.S. gross domestic product.

Converting to WWS would further eliminate ~$3.3 (1.9-7.1) trillion per year in 2050 global warming costs to the world due to U.S. greenhouse gas emissions. These plans will result in the average person in the U.S. in 2050 saving ~$260 (190-320) per year in energy costs (2013 dollars), $1,500 (210-6,000) per year in health costs, and $8,300 (4,700-17,600) per year in climate costs for a total annual per capita savings of $10,060 (5,100-23,920).

Uncertainties remain in terms of the range of energy, health, and climate costs we estimate in our analysis. These ranges may miss costs impacted by unforeseen political/social events. As such, the estimates should be reviewed periodically. However, even recognizing such uncertainties, I conclude to a strong degree of scientific certainty that transitioning to 100% WWS is in the economic best interest of the United States.

Transitioning to 100% WWS will allow the United States to produce as much power as it uses in the annual average at present, thereby reducing its reliance on international competition for energy, potentially reducing international conflict and increasing energy stability within the United States. In addition, the economic benefits of transitioning to 100% WWS would flow toward the citizens of the United States, as we would not be required to purchase fossil fuels from other countries.

Transitioning to 100% WWS will increase access to distributed energy, providing easier and more access to energy for those living in remote areas.

Transitioning to 100% WWS will reduce the risk of large-scale system disruption due to large power plant outages and physical terrorism (but not necessarily due to cyberattack) because much of the world power supply will be decentralized into more, smaller power sources.

Based on the scientific results presented, current barriers to implementing the WWS roadmaps are neither technical nor economic. They are social and political. Such barriers are due partly to the fact that most people are unaware of what changes are possible, what technology is available, and how they will benefit from a transition to WWS in their own lives and partly due to the fact that many with a financial interest in the current energy industry resist change. Because the benefits of converting (reduced global warming and air pollution, new jobs and stable energy prices) far exceed the costs, converting has little downside.

2. What is Needed to Decrease Atmospheric CO_2 to 350 ppm by 2100

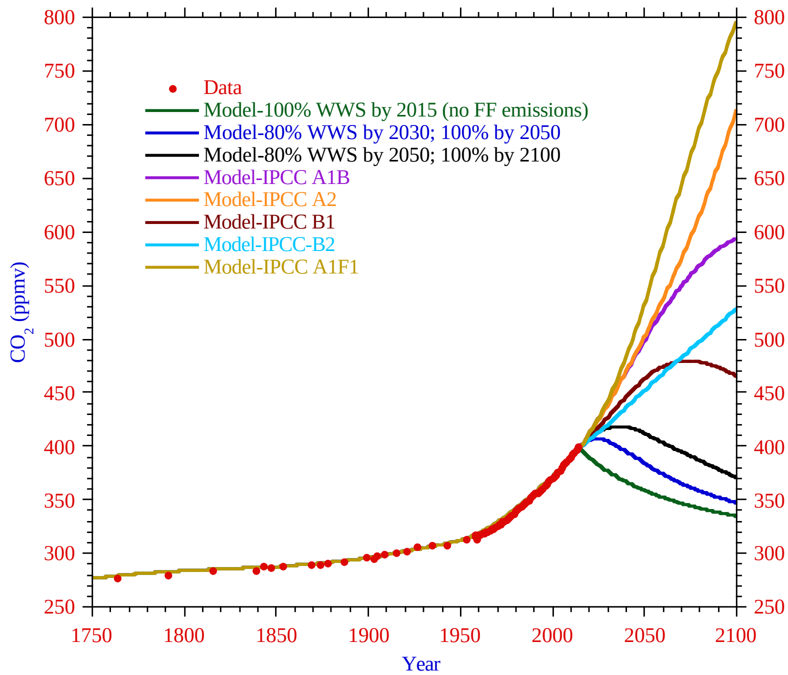
Transitioning 80% of the United States and the world's energy and land-use change emissions to WWS by 2030 and 100% by 2050 is consistent with a trajectory to allow atmospheric CO_2 levels to decrease to near 350 ppm by 2100.

Matthews (2016) estimates the global emission limits to keeping temperature increases under 1.5°C with probabilities of 67% and 50% as 2400 Gt-CO_2 and 2625 Gt-CO_2, respectively.

Between 1870 and the end of 2015, a cumulative ~2050 Gt-CO_2 was emitted globally from fossil-fuel combustion, cement manufacturing, and land use change. (Mathews, 2016). This suggests no more than 350-575 Gt-CO_2 can be emitted for a 67-50% probability of keeping post-1870 warming under 1.5°C. Given the current and projected global emission rate of CO_2, it is necessary to cut energy- and land-use change emissions yearly until emission cuts reach 80% by 2030 and 100% by 2050 to limit warming to 1.5°C with a probability of between 50% and 67%.

Figure 4 illustrates the possible impact on global atmospheric carbon dioxide levels of an 80% conversion to WWS by 2030 and 100% conversion by 2050 as well as possible impacts from less aggressive emission reductions. The 100% by 2050 scenario can reduce CO_2 to near 350 ppm by 2100, a level last measured in the atmosphere around 1988. All IPCC (2000) emission scenarios result in CO_2 levels in 2100, ranging from 460 to 800 ppm. Such scenarios are certain to drive temperatures dangerously higher. A WWS scenario for the United States is essential for stabilizing and ultimately reducing temperatures over the long-term.

Figure 4. Comparison of historic (1751-2014) observed CO_2 mixing ratios (ppmv) from the Siple ice core (Neftel et al., 1994) and the Mauna Loa Observatory (Tans and Keeling, 2015) with GATOR-GCMOM model results (Jacobson, 2005) for the same period plus model projections from 2015-2100 for five Intergovernmental Panel on Climate Change (IPCC) scenarios (IPCC, 2000) and three WWS cases: an unobtainable 100% WWS by 2015 case, an 80% WWS by 2030 and 100% by 2050 case (from Figure 1 above), and a less-aggressive 80% by 2050 and 100% by 2100 case.



The model is set up as in Jacobson (2005) with two columns (one atmospheric box over 38 ocean layers plus one atmospheric box over land). It treats full ocean chemistry in all layers, vertical ocean diffusion with canonical diffusion coefficients, ocean removal of calcium carbonate for rock formation, gas-ocean transfer, and emissions from fossil fuels. It also accounts for photosynthesis, plant and soil respiration, and removal of carbon dioxide from the air by weathering. Fossil-fuel emissions from 1751-1958 are from Boden et al. (2011), from 1959-2014 are from Le Quere et al. (2015), and for 2015 onward from the WWS scenarios scaled from 2014 emission and from the individual IPCC scenarios. Land use change emissions per year are 300 Tg-C/yr for 1751-1849, from Houghton (2012) for 1850-1958, from Le Quere et al. (2015) for 1959-2014, from the IPCC (2000) A1B scenario for the WWS cases for 2015-2100, and from the individual IPCC scenarios for the remaining cases. The net carbon sink over land from 1751-2100 is calculated from the time-dependent photosynthesis, respiration, and weathering processes mentioned.

3. List of Technology Replacements and Timelines for Their Implementation

Below is a list of electric appliances, transportation options, and WWS power generators that are needed to transition to 100% WWS. Most of these technologies are available today, and the rest (e.g., for aircraft and ships in particular) are currently being designed to transform the energy infrastructure of the United States. The list is not a complete list, but demonstrates that 95% of the technological solutions for a complete transition to WWS by 2050 already exist. Future

innovations over the next 30 years and beyond will very likely provide even more technological mechanisms to facilitate the remaining transition to 100% WWS for all purposes by 2050.

A. Technology Replacements

i. Increase Energy Efficiency / Reduce Energy Demand

a. Increase efficiency in buildings through:

Lighting:

- LED lighting
- Advanced lighting controls

Appliances:

- High efficiency pumps and motors
- High efficiency commercial appliances (refrigerators, washers, dryers)
- Energy efficient residential appliances (refrigerators, water heaters, etc.)
- Variable refrigerant flow

Heating and cooling efficiency in buildings through:

- Programmable thermostats
- Improved wall, floor, ceiling, and pipe insulation
- High-efficiency double- and triple-pane windows
- Energy efficient framing practices
- Passive solar design
- Sealing doors, windows, walls, outlets, and fireplaces to reduce heat / cold loss
- Evaporative cooling systems
- Ductless heat pumps for heating and air conditioning
- Water-cooled heat exchanging
- Night ventilation cooling
- Passive ventilation design
- Combined space and water heating
- Air flow management
- Heat recovery ventilation systems
- Building energy monitors to identify opportunities to reduce wasted energy

Water efficiency:

- High efficiency residential and commercial water fixtures
- High efficiency irrigation systems
- Greywater re-use systems

b. Reduced transportation demand through:

- Telecommuting rather than commute by car
- Improved biking infrastructure
- Improved pedestrian infrastructure

- Improved public transportation
- Transportation Demand Management programs that support adoption of low-carbon transportation practices
- Improved carpooling and ride-sharing programs and technologies
- Urban land use practices to reduce transportation demand (i.e. mixed use development, increased residential densities)

c. Improved vehicle efficiency through:

- Low rolling resistance tires
- Lightweight materials (i.e. carbon fiber, aluminum, fiberglass)
- Regenerative braking systems
- High efficiency settings or dashboard fuel efficiency displays

ii. WWS Electric Power Generators

- Onshore/offshore wind turbines
- Solar photovoltaics (PV) for rooftops and power plants
- Concentrated Solar Power (CSP) plants
- Geothermal power plants for electricity
- Tidal turbines
- Wave devices
- Existing large hydroelectric reservoirs used more efficiently
- Small hydroelectric reservoirs
- In-stream hydroelectric turbines

iii. Low-Temperature Heat Generators

- Geothermal heat pumps
- Natural geothermal heating
- Solar thermal collection devices for heat

iv. Electricity Storage

- CSP with storage (either molten salt or phase-change material)
- Pumped hydroelectric storage
- Hydroelectric power plant reservoirs
- Batteries

v. Heat Storage Devices

- Hot water tanks
- Rocks stored underground
- Thermal walls

vi. Cold Storage Devices

- Chilled water tanks
- Ice storage

vii. Hydrogen Storage Devices

- Electrolyzers to produce hydrogen from electricity
- Electric compressors to compress hydrogen
- Tanks to store hydrogen for transportation primarily

viii. Demand Response

- Technology to enable remote start up and shut down of appliances and equipment that have flexible demand (i.e. water heaters, HVAC equipment, electric vehicles)
- Utilities provide incentives for industry, companies, and individuals to shift their electricity use for certain uses and processes to non-peak times of day or night – Time of Use electricity pricing

ix. Electric Vehicles

- Light-, medium-, and heavy-duty on-road automobiles
- Short-distance trucks, buses trains, ships, aircraft
- Motorcycles
- Non-road vehicles
- Construction equipment
- Agricultural equipment
- Forklifts

x. Hydrogen Fuel Cell/Electric Hybrid Vehicles

- Long-distance trucks
- Buses
- Long-distance trains
- Long-distance ships
- Long-distance aircraft
- Construction equipment
- Agricultural equipment

xi. Electric Car Charging Infrastructure

- Home car chargers
- Chargers installed in parking garages and on streets

xii. High-Temperature Industrial Equipment

- Electric arc furnaces
- Dielectric heaters
- Electric induction furnaces

xiii. Electric Appliances to Replace Gas or Gasoline

- Heat pump air and water heaters
- Electric induction cooktop stoves
- Electric dryers
- Electric leaf blowers

- Electric lawnmowers
- Electric water sprayers
- Electric fans

xiv. Long-Distance Transmission

- High-voltage direct-current (HVDC) lines

Whereas, much new WWS infrastructure can be installed upon natural retirement of BAU infrastructure, new policies are needed to force remaining existing infrastructure to retire early to allow the complete conversion to WWS by 2050. Because the air-pollution and climate-impact benefits (avoided costs) (28.5 (11.2-72) ¢/kWh-BAU-all-energy) resulting from closing BAU plants early far exceed the annualized remaining *net* asset value of such plants (the difference between the annualized capital cost and the annualized salvage or re-use value) divided by annual energy produced, and because net jobs increase upon replacing BAU plants, retiring them early results in large net health, employment, and climate benefits to society.

B. Timelines for Transitioning Individual Sectors

The overall timeline proposed for transitioning to 100% WWS is 80% by 2030 and 100% by 2050. To meet this timeline, rapid transitions are needed in each technology sector. Below is a list of proposed transformation timelines for individual sectors.

> ***Development of super grids and smart grids:*** as soon as possible, the United States should develop long-term power-transmission-and-distribution systems to provide "smart" management of energy demand and supply at all scales, from local to international, with a 100% WWS system. This allows supply and demand to be optimized.
>
> ***Power plants*:** by 2020 at the latest, no more construction of new coal, nuclear, natural gas, or biomass fired power plants; all new power plants built should be WWS.
>
> ***Storage:*** starting immediately, heat, cold, and electric storage technologies should be deployed. Heat storage technologies include underground storage in rocks, storage in hot water tanks, and storage in thermal mass (e.g., wax, cement blocks). Cold storage includes primarily storage in ice and water. Electric storage includes storage in concentrated solar power, pumped hydroelectric power, batteries, and in existing hydroelectric reservoirs. Other types of storage are also possible.
>
> ***Heating, drying, and cooking in the residential and commercial sectors*:** by 2020, all new devices, appliances, and machines should be electric.
>
> ***Industrial heat*:** by 2023, all new high-temperature heating equipment for industrial applications should be electric.

***Large-scale waterborne freight transport*:** by 2020-2025, all new ships should be electrified and/or use electrolytic hydrogen, all new port operations should be electrified, and port retro-electrification should be well underway.

***Rail and bus transport*:** by 2025, all new trains and buses should be electrified. This requires changing the supporting energy-delivery infrastructure and the manufacture method of transportation equipment.

***Off-road transport, small-scale marine*:** by 2025 to 2030, all new production should be electrified.

***Long-distance heavy-duty truck transport*:** by 2025 to 2030, all new heavy-duty trucks and buses should be electric or hydrogen fuel cell-electric hybrids.

Light-duty on-road transport: by 2025-2030, all new light-duty on-road vehicles should be electric.

***Short-haul aircraft*:** by 2035, all new small, short-range aircraft should be electric.

***Long-haul aircraft*:** by 2040, all remaining new aircraft should be hydrogen fuel cell-electric hybrids.

During the transition, conventional fuels and existing WWS technologies are needed to produce the remaining WWS infrastructure. However, much of the conventional energy would be used in any case to produce conventional power plants and automobiles if the plans proposed here were not implemented. Further, as the fraction of WWS energy increases, conventional energy generation will decrease, ultimately to zero, at which point all new WWS devices will be produced with existing WWS. In sum, the creation of WWS infrastructure may result in a temporary increase in emissions before they are ultimately reduced to zero.

4. Recommended First Steps and Potential Policies

Whereas, much new WWS infrastructure can be installed upon natural retirement of BAU infrastructure, new policies are needed to encourage remaining existing infrastructure to retire early to allow the complete conversion to WWS. Because the annual air-pollution and climate-impact benefits (avoided costs), as quantified here, resulting from closing BAU plants early far exceed the annualized remaining *net* asset value of such plants (the difference between the annualized capital cost and the annualized salvage or re-use value), and because net jobs increase upon replacing BAU plants, retiring them early results in large net benefits to society.

5. Why Nuclear, Biofuels, and Coal with Carbon Capture are Not Included

While some people have suggested that energy options aside from WWS, such as nuclear power, coal with carbon capture and sequestration (coal-CCS), and biofuels, can play a role in solving these problems, all four technologies, while better in several respects than fossil fuel technologies, have some disadvantages relative to fossil fuel technologies and significant

disadvantages relative to WWS technologies. These advantages/disadvantages are listed below and then explained in more detail below that.

With respect to some of the disadvantages, it is important to note that because we must reduce emissions 80% by 2030 (thus only 12 years from 2018), we do not recommend power plant technologies that cannot be installed within the next few years.

Nuclear power

Advantages

- Low carbon and air pollution relative to fossil fuels.
- Requires only modest land use.

Disadvantages

- Requires 10-19 years between planning and operation versus 2-5 years for wind/solar.
- Expensive; cannot be built without significant financial support and insurance guarantee from government.
- Carries weapons proliferation risk.
- Carries meltdown risk (1.5% of all reactors built to date have melted down).
- Nuclear waste disposal issue (where to put the waste).
- Significant water is required for cooling with current and future technology.
- Nuclear material mining risks.
- Nuclear material transportation risks.
- 6-23 times the carbon emissions of wind power per unit energy generated.
- Not a renewable resource.
- Potential terrorism target.

Coal with carbon capture

Advantages

- Less carbon dioxide emissions than coal without carbon capture.
- Keeps coal miners employed in mining.

Disadvantages

- Requires 25% more energy than regular coal → 25% more air pollution emissions than regular coal because carbon capture equipment reduces only carbon dioxide.
- Still produces 50-60 times more CO_2 per unit energy than wind because it doesn't reduce CO_2 from mining or transporting coal, which is one-third of the emissions associated with coal power generation.
- Still results in land/habitat destruction due to coal mining.
- Still results in black lung disease to coal miners.
- Much more expensive than wind or solar power.
- Requires a minimum of 6-9 years between planning and operation versus 2-5 years for wind/solar.
- Coal-CCS can only be placed near specific geological formations.
- Long-term geologic storage of CO_2 is unproven.

- CO_2 stored underground has potential to leak.
- Not a renewable resource.

Biofuels

Advantages

- Carbon produced from burning a biofuel can be recaptured during regrowth of the biofuel.
- Biofuel combustion emits less of some chemicals than gasoline or diesel combustion.
- Biofuels can sometimes be substituted directly for fossil fuels in some automobiles, for example.

Disadvantages

- Biofuels require a significant amount of energy to produce, and a lot of that energy can be from fossil fuel combustion.
- Biofuel combustion emits more of some chemicals than gasoline or diesel combustion.
- Overall ozone production and mortality from burning ethanol as a fuel exceeds that from burning gasoline in the United States.
- The land required for growing biocrops is enormous.
- Solar PV produces 20 times more electricity than a biocrop produces energy over the same amount of land.
- Using land for food instead of fuel raises the price of food and spurs deforestation in parts of the world to create more land for biocrops.

With respect to the cost of nuclear and coal-CCS, the Intergovernmental Panel on Climate Change (IPCC) (2014) states (Section 7.8.2), "*Without support from governments, investments in new nuclear power plants are currently generally not economically attractive within liberalized markets,…"*

Similarly, Freed et al. (2017), who are strong nuclear advocates, state, "*…there is virtually no history of nuclear construction under the economic and institutional circumstances that prevail throughout much of Europe and the United States*."

Further, Cooper (2016), who compared WWS with nuclear and CCS scenarios, concluded, "*Neither fossil fuels with CCS or nuclear power enters the least-cost, low-carbon portfolio*."

IPCC (2014) further states that, with high penetrations of renewable energy (RE), nuclear and CCS are not efficient (Section 7.6.1.1), "*…high shares of variable RE power…may not be ideally complemented by nuclear, CCS,…"*

With respect to the other disadvantages of nuclear, IPCC (2014, p. 517) concludes that there is "*robust evidence"* and *"high agreement*" that "*Barriers to and risks associated with an increasing use of nuclear energy include operational risks and the associated safety concerns, uranium mining risks, financial and regulatory risks, unresolved waste management issues, nuclear weapons proliferation concerns, and adverse public opinion."* As such, expanding the

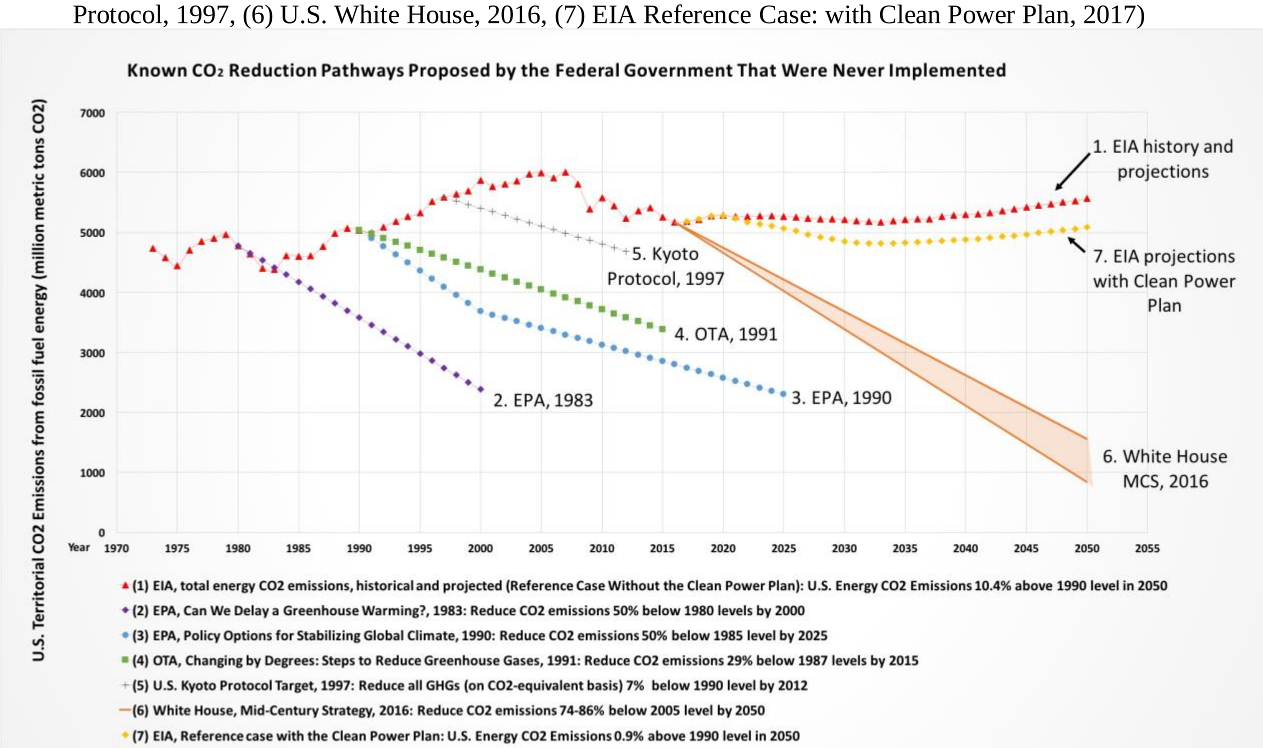
use of nuclear to countries where it doesn't exist may increase weapons proliferation and meltdown risks. Wind, water, and solar power have none of these risks. More advanced nuclear cannot be evaluated until it is commercialized, but it does not exist today.

With respect to the time lag between planning and operation of nuclear versus wind/solar, the air pollution emissions of nuclear versus coal-CCS versus biofuels versus wind/solar, please see Jacobson (2007, 2009).

6. Historical WWS Technological Feasibility

The United States could have begun the WWS transition by at least the late 1970s and early 1980s. In my expert opinion, had government promoted a climate-safe national energy policy at that time, the proportion of our nation's energy system powered by WWS would today be much greater than it is currently in my estimation. For example, the graph in **Figure 5** below shows several historical examples of the U.S. government making recommendations, roadmaps, or plans since the early 1980s to decarbonize the national energy system, none of which was implemented. Notwithstanding their knowledge of climate change, and the alternative energy systems available to the country, the Federal Defendants chose to continue a fossil fuel energy system, which still supplies the majority of our energy today across all sectors. The red line shows actual and projected business as usual US emissions by the EIA under the Trump administration, which diverge substantially from the other recommended energy emission pathways.

Figure 5. Known CO_2 reduction pathways proposed by the Federal Government that were never implemented. ((1) EIA Reference Case, 2017 (2) EPA, 1983, (3) EPA, 1990, (4) OTA 1991, (5) Kyoto Protocol, 1997, (6) U.S. White House, 2016, (7) EIA Reference Case: with Clean Power Plan, 2017)



Other Examples:

- California developed the first three major wind farms worldwide in the late 1970s and early 1980s. These were Altamont Pass, Tehachapi, and San Gorgonio Pass. However, U.S. national policy shifted, and further growth of wind was slowed substantially for 1-2 decades. During that period, the center of wind farm development and manufacturing moved to Europe.

- Similarly, burgeoning U.S. policy in the 1970s encouraged solar energy expansion, but dominant U.S. policies that favored traditional fossil fuels squeezed out solar growth in the 1980s and 1990s. Only in the last decade has solar begun to grow substantially. In a December 5, 1978 Department of Energy Domestic Policy Review of Solar Energy Report to the White House, Defendant DOE projected that technical capacity for solar penetration by the year 2000 was 26-31% of national energy supply (Schlesinger 1978). The same report also confirmed the inefficiency of the energy system where 56% of annual energy use was consumed in conversion, transmission and end-use losses, not in actual energy use. The report confirms that widespread use of solar energy, which was technically available even in the 1970s was "hindered by Federal and state policies and market imperfections that effectively subsidize competing energy sources." The lack of federal R&D and other support, which was largely given to fossil fuels, limited the "long-term contribution of solar energy to the nation's energy supply." (Schlesinger 1978).

- Electric cars have been around for over 180 years (since 1837). The first U.S. electric car was built in 1890. By 1900, 34,000 cars, or 38% of the U.S. fleet was electric. However, their popularity declined in the 1910s due to greater range of fossil fuel cars. Electric cars only began to re-emerge in the U.S. in the 1990s following a push by the California Air Resources Board to reduce emissions. But, pressure by the oil industry combined with U.S. policy that supported the internal combustion engine and fossil fuels, not electric vehicles, caused manufacturers to stop producing and even destroying electric cars. After the development of the Toyota Prius, Tesla began working on an electric car in 2004, successfully producing a long-distance Roadster in 2008. In my expert opinion, if government had given support to electric cars during any decade prior to the mid- to- late 2000s, I believe, the percent of the U.S. automobile market that is electric would be significantly higher than today.

- It is my expert opinion that if the policies of the United States had encouraged more subsidies and R&D for renewable energy, efficiency, electric appliances, and electric cars rather than subsidies and other support for fossil fuels, our country would be a lot further toward a renewable-powered energy system today than it is, the amount of carbon dioxide pollution emitted would be substantially less, and the harms from climate change would not be as severe as they are today and are projected to be in the near and long-term.

CONCLUSION AND RECOMMENDATION

In sum, I conclude that electrification and use of direct heat in all energy sectors in the United States, and providing the electricity and direct heat with 100% wind, water, and sunlight (WWS) by 2050, with 80% by 2030, is technologically and economically feasible. Use of WWS technologies may be the only way to solve the climate, air pollution, and energy security problems in a timely manner. They also involve the least risk of collateral damage and serve multiple public interests, including creating more full-time, long-term jobs than lost, reducing reliance on the international search for energy, providing energy security, and reducing substantial air pollution health and climate problems. Given that 4-7 million people currently die premature each year worldwide due to fossil fuel pollution, including 62,000 (19,000-115,000) in the United States, and climate is changing rapidly due to the increase in human-emitted gases and particles into the atmosphere, the rapid deployment of a 100% WWS solution is important and practical for solving these problems simultaneously. The bottom line is that it is technically and economically feasible to transition off of fossil fuels by 2050 and supply our energy needs with 100% WWS. The primary barrier is the lack of government direction to move energy policy in the WWS direction and government policies and actions that continue to favor a fossil-fuel based energy system.

In my expert opinion, if the U.S. defendants in this case are ordered to plan for, and implement, a 100% WWS transition by 2050, it is feasible to develop such a plan and almost all the technology is available to carry out the plan quickly in a cost-effective manner.

Signed this 6th day of April, 2018 in Palo Alto, California.

Mark Z Jacobson

Mark Jacobson, Ph.D.

EXHIBIT A: CV

MARK Z. JACOBSON
Department of Civil & Environmental Engineering
Yang and Yamazaki Bldg., Room 397
Stanford University
Stanford, CA 94305-4020, USA

Tel: (650) 723-6836
Fax: (650) 723-7058
Email: jacobson@stanford.edu
Web: www.stanford.edu/group/efmh/jacobson/

<u>Professional Preparation</u>

Stanford University, Stanford, CA; Civil Engineering B.S., with distinction, 1988
Stanford University, Stanford, CA; Economics B.A., with distinction, 1988
Stanford University, Stanford, CA; Environmental Engineering M.S., 1988
UCLA, Los Angeles, CA; Atmospheric Sciences M.S., 1991
UCLA, Los Angeles, CA; Atmospheric Sciences Ph.D., 1994

<u>Professional Appointments</u>

Stanford University Atmosphere/Energy Program Director/co-founder, 2004-present
Stanford University Energy Resources Engineering Professor by Courtesy, 2007-2010
Stanford University Civil & Environmental Engineering Professor, 2007-present
Stanford University Civil & Environmental Engineering Associate Professor, 2001-2007
Stanford University Civil & Environmental Engineering Assistant Professor, 1994 2001

Mark Z. Jacobson's career has focused on better understanding air pollution and global warming problems and developing large-scale clean, renewable energy solutions to them. Toward that end, he has developed and applied three-dimensional atmosphere-biosphere-ocean computer models and solvers to simulate air pollution, weather, climate, and renewable energy. He has also developed roadmaps to transition states and countries to 100% clean, renewable energy for all purposes and computer models to examine grid stability in the presence of high penetrations of renewable energy.

To date, he has published two textbooks of two editions each and 152 peer-reviewed journal articles. He has testified four times for the U.S. Congress. Nearly a thousand researchers have used computer models he has developed. In 2005, he received the American Meteorological Society Henry G. Houghton Award for "significant contributions to modeling aerosol chemistry and to understanding the role of soot and other carbon particles on climate." In 2013, he received an American Geophysical Union Ascent Award for "his dominating role in the development of models to identify the role of black carbon in climate change" and the Global Green Policy Design Award for the "design of analysis and policy framework to envision a future powered by renewable energy." In 2016, he received a Cozzarelli Prize from the *Proceedings of the National Academy of Sciences* for "outstanding scientific excellence and originality" in his paper on a solution to the U.S. grid reliability problem with 100% penetration of wind, water, and solar power for all purposes. He has also served on the Energy Efficiency and Renewables advisory committee to the U.S. Secretary of Energy and was invited to talk about his world and U.S. clean-energy plans on the Late Show with David Letterman.

Publications 2007-2018

1. Jacobson, M.Z., Effects of ethanol (E85) versus gasoline vehicles on cancer and mortality in the United States, *Environ. Sci. Technol.*, *41* (11), 4150-4157, doi:10.1021/es062085v, 2007, www.stanford.edu/group/efmh/jacobson/Articles/I/E85vWindSol.
2. Jacobson, M.Z., Y.J. Kaufmann, Y. Rudich, Examining feedbacks of aerosols to urban climate with a model that treats 3-D clouds with aerosol inclusions, *J. Geophys. Res*., 112, D24205, doi:10.1029/2007JD008922, 2007, www.stanford.edu/group/efmh/jacobson/Articles/III/IIIe.html.
3. Jacobson, M.Z, On the causal link between carbon dioxide and air pollution mortality, *Geophysical Research Letters*, *35*, L03809, doi:10.1029/2007GL031101, 2008, www.stanford.edu/group/efmh/jacobson/Articles/V/Ve.html.
4. Jacobson, M.Z., Effects of wind-powered hydrogen fuel cell vehicles on stratospheric ozone and global climate, *Geophys. Res. Lett*., 35, L19803, doi:10.1029/2008GL035102, 2008, www.stanford.edu/group/efmh/jacobson/Articles/I/fuelcellhybrid.html.

5. Jacobson, M.Z., The short-term effects of agriculture on air pollution and climate in California, *J. Geophys. Res.*, 113, D23101, doi:10.1029/2008JD010689, 2008, www.stanford.edu/group/efmh/jacobson/Articles/IV/IVb.html.
6. Jacobson, M.Z., Review of solutions to global warming, air pollution, and energy security, *Energy & Environmental Science*, 2, 148-173, doi:10.1039/b809990c, 2009, www.stanford.edu/group/efmh/jacobson/Articles/I/revsolglobwarmairpol.htm.
7. Jacobson, M.Z., and D.G. Streets, The influence of future anthropogenic emissions on climate, natural emissions, and air quality, *J. Geophys. Res*., 114, D08118, doi:10.1029/2008JD011476, 2009, www.stanford.edu/group/efmh/jacobson/Articles/VII/Influence_of_futureanthropogenicemissions.html
8. Jacobson, M.Z., Effects of biofuels vs. other new vehicle technologies on air pollution, global warming, land use, and water, *Int. J. Biotechnology*, 11, 14-59, 2009, www.stanford.edu/group/efmh/jacobson/Articles/Others/BiofuelFinPapMZJIntJBiotechnol08.pdf.
9. Jacobson, M.Z., and M.A. Delucchi, A path to sustainable energy by 2030, *Scientific American*, November 2009 (cover story), www.stanford.edu/group/efmh/jacobson/Articles/I/susenergy2030.html.
10. Jacobson, M.Z., The enhancement of local air pollution by urban CO_2 domes, *Environ. Sci. Technol.*, *44*, 2497-2502, doi:10.1021/es903018m, 2010, www.stanford.edu/group/efmh/jacobson/Articles/V/urbanCO2domes.html.
11. Jacobson, M.Z., Short-term effects of controlling fossil-fuel soot, biofuel soot and gases, and methane on climate, Arctic ice, and air pollution health, *J. Geophys. Res.*, *115*, D14209, doi:10.1029/2009JD013795, 2010, www.stanford.edu/group/efmh/jacobson/Articles/VIII/controlfossilfuel.html
12. Jacobson, M.Z., and D.L. Ginnebaugh, Global-through-urban nested three-dimensional simulation of air pollution with a 13,600-reaction photochemical mechanism, *J. Geophys. Res*., *115*, D14304, doi:10.1029/2009JD013289, 2010, www.stanford.edu/group/efmh/jacobson/Articles/V/3Dgas-photochem.html.
13. Jacobson, M.Z., Numerical Solution to Drop Coalescence/Breakup With a Volume-Conserving, Positive-Definite, and Unconditionally-Stable Scheme, *J. Atmos. Sci*., *68*, 334-346, doi:10.1175/2010JAS3605.1, 2011, www.stanford.edu/group/efmh/jacobson/Articles/IX/BreakupPaper1010.html.
14. Jacobson, M.Z., and M.A. Delucchi, Providing all Global Energy with Wind, Water, and Solar Power, Part I: Technologies, Energy Resources, Quantities and Areas of Infrastructure, and Materials, *Energy Policy*, 39, 1154-1169, doi:10.1016/j.enpol.2010.11.040, 2011, www.stanford.edu/group/efmh/jacobson/Articles/I/susenergy2030.html.
15. Jacobson, M.Z., J.T. Wilkerson, A.D. Naiman, and S.K. Lele, The effects of aircraft on climate and pollution. Part I: Numerical methods for treating the subgrid evolution of discrete size- and composition-resolved contrails from all commercial flights worldwide, *J. Comp. Phys*., 230, 5115-5132, doi:10.1016/j.jcp.2011.03.031, 2011, http://www.stanford.edu/group/efmh/jacobson/Articles/VIII/aircraftflights.html.
16. Jacobson, M.Z., and J.E. Ten Hoeve, Effects of urban surfaces and white roofs on global and regional climate, *J. Climate*, *25*, 1028-1044, doi:10.1175/JCLI-D-11-00032.1, 2012, www.stanford.edu/group/efmh/jacobson/Articles/IV/IVc.html.
17. Jacobson, M.Z., Investigating cloud absorption effects: Global absorption properties of black carbon, tar balls, and soil dust in clouds and aerosols, *J. Geophys. Res*., *117*, D06205, doi:10.1029/2011JD017218, 2012, www.stanford.edu/group/efmh/jacobson/Articles/VII/CloudAbsorption.html.
18. Jacobson, M.Z., J.T. Wilkerson, S. Balasubramanian, W.W. Cooper, Jr., and N. Mohleji, The effects of rerouting aircraft around the Arctic Circle on Arctic and global climate, *Climatic Change*, 115, 709-724, doi:10.1007/s10584-012-0462-0, 2012, www.stanford.edu/group/efmh/jacobson/Articles/VIII/aircraftflights.html.
19. Jacobson, M.Z., and C.L. Archer, Saturation wind power potential and its implications for wind energy, *Proc. Nat. Acad. Sci*., *109*, 15,679-15,684, doi:10.1073/pnas.1208993109, 2012, www.stanford.edu/group/efmh/jacobson/Articles/I/windfarms.html.
20. Jacobson, M.Z., R.W. Howarth, M.A. Delucchi, S.R. Scobies, J.M. Barth, M.J. Dvorak, M. Klevze, H. Katkhuda, B. Miranda, N.A. Chowdhury, R. Jones, L. Plano, and A.R. Ingraffea, Examining the feasibility of converting New York State's all-purpose energy infrastructure to one using wind, water, and sunlight, *Energy Policy*, 57, 585-601, 2013, www.stanford.edu/group/efmh/jacobson/Articles/I/susenergy2030.html.
21. Jacobson, M.Z., J.T. Wilkerson, A.D. Naiman, and S.K. Lele, The effects of aircraft on climate and pollution. Part II: 20-year impacts of exhaust from all commercial aircraft worldwide treated individually at the subgrid scale, *Faraday Discussions*, *165*, 369-382, doi:10.1039/C3FD00034F, 2013, http://www.stanford.edu/group/efmh/jacobson/Articles/VIII/aircraftflights.html.
22. Jacobson, M.Z., C.L. Archer, and W. Kempton, Taming hurricanes with arrays of offshore wind turbines, *Nature Climate Change*, *4*, 195-200, doi: 10.1038/NCLIMATE2120, 2014, http://web.stanford.edu/group/efmh/jacobson/Articles/I/WindHurricane/WindHurric.html.

23. Jacobson, M.Z., M.A. Delucchi, A.R. Ingraffea, R.W. Howarth, G. Bazouin, B. Bridgeland, K. Burkhart, M. Chang, N. Chowdhury, R. Cook, G. Escher, M. Galka, L. Han, C. Heavey, A. Hernandez, D.F. Jacobson, D.S. Jacobson, B. Miranda, G. Novotny, M. Pellat, P. Quach, A. Romano, D. Stewart, L. Vogel, S. Wang, H. Wang, L. Willman, T. Yeskoo, A roadmap for repowering California for all purposes with wind, water, and sunlight, *Energy*, *73*, 875-889, doi:10.1016/j.energy.2014.06.099, 2014, http://www.stanford.edu/group/efmh/jacobson/Articles/I/susenergy2030.html.
24. Jacobson, M.Z., Effects of biomass burning on climate, accounting for heat and moisture fluxes, black and brown carbon, and cloud absorption effects, *J. Geophys. Res*., *119*, 8980-9002, doi:10.1002/2014JD021861, 2014, http://web.stanford.edu/group/efmh/jacobson/Articles/VIII/bioburn/index.html.
25. Jacobson, M.Z., S.V. Nghiem, A. Sorichetta, and N. Whitney, *Ring of impact* from the mega-urbanization of Beijing between 2000 and 2009, *J. Geophys. Res*., *120*, 5740-5756, doi:10.1002/2014JD023008, 2015, http://web.stanford.edu/group/efmh/jacobson/Articles/IV/IVd.html.
26. Jacobson, M.Z., M.A. Delucchi, G. Bazouin, Z.A.F. Bauer, C.C. Heavey, E. Fisher, S. B. Morris, D.J.Y. Piekutowski, T.A. Vencill, T.W. Yeskoo, 100% clean and renewable wind, water, sunlight (WWS) all-sector energy roadmaps for the 50 United States, *Energy and Environmental Sciences*, *8*, 2093-2117, doi:10.1039/C5EE01283J, 2015, http://web.stanford.edu/group/efmh/jacobson/Articles/I/WWS-50-USState-plans.html, http://pubs.rsc.org/en/content/articlelanding/2014/ee/c5ee01283j#!divAbstract
27. Jacobson, M.Z., M.A. Delucchi, M.A. Cameron, and B.A. Frew, A low-cost solution to the grid reliability problem with 100% penetration of intermittent wind, water, and solar for all purposes, *Proc. Nat. Acad. Sci*., *112* (*49*), 15,060-15,065 doi: 10.1073/pnas.1510028112, 2015, http://web.stanford.edu/group/efmh/jacobson/Articles/I/CombiningRenew/combining.html.
28. Jacobson, M.Z., M.A. Delucchi, G. Bazouin, M.J. Dvorak, R. Arghandeh, Z. A.F. Bauer, A. Cotte, G.M.T.H. de Moor, E.G. Goldner, C. Heier, R.T. Holmes, S.A. Hughes, L. Jin, M. Kapadia, C. Menon, S.A. Mullendore, E.M. Paris, G.A. Provost, A.R. Romano, C. Srivastava, T.A. Vencill, N.S. Whitney, and T.W. Yeskoo, A 100% wind, water, sunlight (WWS) all-sector energy plan for Washington State, *Renewable Energy*, *86*, 75-88 2016, http://web.stanford.edu/group/efmh/jacobson/Articles/I/WWS-50-USState-plans.html.
29. Jacobson, M.Z., M.A. Delucchi, Z.A.F. Bauer, S.C. Goodman, W.E. Chapman, M.A. Cameron, Alphabetical: C. Bozonnat, L. Chobadi, H.A. Clonts, P. Enevoldsen, J.R. Erwin, S.N. Fobi, O.K. Goldstrom, E.M. Hennessy, J. Liu, J. Lo, C.B. Meyer, S.B. Morris, K.R. Moy, P.L. O'Neill, I. Petkov, S. Redfern, R. Schucker, M.A. Sontag, J. Wang, E. Weiner, A.S. Yachanin, 100% clean and renewable wind, water, and sunlight (WWS) all-sector energy roadmaps for 139 countries of the world, *Joule*, *1*, 2017, http://web.stanford.edu/group/efmh/jacobson/Articles/I/WWS-50-USState-plans.html
30. Jacobson, M.Z., M.A. Delucchi, M.A. Cameron, and B.V, Mathiesen, Matching demand with supply at low cost among 139 countries within 20 world regions with 100% intermittent wind, water, and sunlight (WWS) for all purposes, *Renewable Energy 123*, 236-248, doi:10.1016/j.renene.2018.02.0092018, 2018 https://web.stanford.edu/group/efmh/jacobson/Articles/I/CombiningRenew/combining.html
31. *Archer, C.L.*, and M.Z. Jacobson, Supplying baseload power and reducing transmission requirements by interconnecting wind farms, *J. Applied Meteorol. and Climatology*, 46, 1701-1717, doi:10.1175/2007JAMC1538.1, 2007, http://www.stanford.edu/group/efmh/winds/index.html.
32. *Archer, C.L*., and M.Z. Jacobson, Geographical and seasonal variability of the global "practical" wind resources, *Applied Geography*, *45*, 119-130, 2013, http://www.stanford.edu/group/efmh/winds/index.html.
33. Bahadur, R., L.M. Russell, M.Z. Jacobson, K.A. Prather, A. Nenes, P.J. Adams, and J.H. Seinfeld, Importance of composition and hygroscopicity of BC particles to the effect of BC mitigation on cloud properties: application to California conditions, *J. Geophys. Res*., *117*, D09204, doi:10.1029/2011JD017265, 2012, http://web.stanford.edu/group/efmh/jacobson/Articles/Others/2012JGRBahadur.pdf
34. Becker, S., B.A. Frew, G.B. Andresen, T. Zeyer, S. Schramm, M Greiner, and M.Z. Jacobson, Features of a fully renewable U.S. electricity-system: Optimized mixes of wind and solar PV and transmission grid extensions, *Energy*, *72*, 443-458, doi:10.1016/j.energy.2014.05.067, 2014, http://web.stanford.edu/group/efmh/jacobson/Articles/Others/BeckerEnergy14.pdf.
35. Becker, S., B.A. Frew, G.B. Andresen, M.Z. Jacobson, S. Schramm, and M. Greiner, Renewable build-up pathways for the U.S.: Generation costs are not system costs, *Energy*, *81*, 437-445, 2015, arxiv.org/pdf/1412.4934, http://web.stanford.edu/group/efmh/jacobson/Articles/Others/BeckerEnergy15.pdf.
36. Boehm, A.B., M.Z. Jacobson, M.J. O'Donnell, M. Sutula, W. Wakefield, and S.B. Weisberg, Ocean acidification science needs for resource managers and users of the North American Pacific coast, *Oceanography*, 28, 170-181, doi:/10.5670/oceanog.2015.40 2015, http://web.stanford.edu/group/efmh/jacobson/Articles/Others/BoehmOceanography15.pdf.

37. Bond, T.C., S.J. Doherty, D.W. Fahey, P.M. Forster, T. Berntsen, O. Boucher, B.J. DeAngelo, M.G. Flanner, S. Ghan, B. Karcher, D. Koch, S. Kinne, Y. Kondo, P.K. Quinn, M.C. Sarofim, M.G. Schultz, M. Schulz, C. Venkataraman, H. Zhang, S. Zhang, N. Bellouin, S.K. Guttikunda, P.K. Hopke, M.Z. Jacobson, J.W. Kaiser, Z. Klimont, U. Lohmann, J.P. Schwarz, D. Shindell, T. Storelvmo, S.G. Warren and C.S. Zender, Bounding the role of black carbon in the climate system: A scientific assessment, *J. Geophys. Res*., *118*, 5380-5552, doi: 10.1002/jgrd.50171, 2013, http://web.stanford.edu/group/efmh/jacobson/Articles/Others/bondJGR2013.pdf.
38. Brasseur, G.P., M. Gupta, B.E. Anderson, S. Balasubramanian, S. Barrett, D. Duda, G. Fleming, P.M. Forster, J. Fluglestvedt, A. Gettelman, R.N. Halthore, S.D. Jacob, M.Z. Jacobson, A. Khodayari, K.-N. Liou, M.T. Lund, R.C. Miake-Lye, P. Minnis, S. Olsen, J.E. Penner, R. Prinn, U. Schumann, H.B. Selkirk, A. Sokolov, N. Unger, P. Wolfe, H.-W. Wong, D.W. Wuebbles, B. Yi, P. Yang, C. Zhou, Impact of aviation on climate: FAA's Aviation Climate Change Research Initiative, *Bulletin of the American Meteorological Society*, doi:10.1175/BAMS-D-13-00089.1, April 2016, 561-583, http://dx.doi.org/10.1175/BAMS-D-13-00089.1
39. Cameron, M.A., M.Z. Jacobson, A.D. Naiman, and S.K. Lele, Effects of plume-scale versus grid-scale treatment of aircraft exhaust photochemistry, *Geophys. Res. Lett.*, *40*, 5815-5820, 2013, http://web.stanford.edu/group/efmh/jacobson/Articles/VIII/13CameronGRL.pdf.
40. Cameron, M.A., M.Z. Jacobson, S. R. H. Barrett, H. Bian, C.-C. Chen, S. D. Eastham, A. Gettelman, A. Khodayari, Q. Liang, D. Phoenix, H. B. Selkirk, N. Unger, D. J. Wuebbles, An Inter-comparative study of the effects of aircraft emissions on surface air quality, *J. Geophys. Res. Atmos.*, *122*, 8325-8344, doi:10.1002/2016JD025594, 2017.
41. Chen, Y., S. Mills, J. Street, D. Golan, A. Post, M.Z. Jacobson, A. Paytan, Estimates of atmospheric dry deposition and associated input of nutrients to Gulf of Aqaba seawater, *J. Geophys. Res*., *112*, D04309, doi:10.1029/2006JD007858, 2007, http://web.stanford.edu/group/efmh/jacobson/Articles/Others/2006JD007858.pdf.
42. Corcoran, B.A., N. Jenkins, and M.Z. Jacobson, Effects of aggregating electric load in the United States, *Energy Policy*, 46, 399-416, doi:10.1016/j.enpol.2012.03.079, 2012, www.stanford.edu/group/efmh/jacobson/Articles/I/CombiningRenew/combining.html.
43. Creamean, J.M., A.P. Ault, J.E. Ten Hoeve, M.Z. Jacobson, G.C. Roberts, and K.A. Prather, Measurements of aerosol chemistry during new particle formation events at a remote rural mountain site, *Environ. Sci. Technol.*, *45*, 8208-8216, doi:10.1021/es103692f, 2011, pubs.acs.org/doi/abs/10.1021/es103692f, http://web.stanford.edu/group/efmh/jacobson/Articles/Others/CreameanEST.pdf.
44. Delucchi, M.Z., and M.Z. Jacobson, Providing all global energy with wind, water, and solar power, Part II: Reliability, System and Transmission Costs, and Policies, *Energy Policy*, 39, 1170-1190, doi:10.1016/j.enpol.2010.11.045, 2011, www.stanford.edu/group/efmh/jacobson/Articles/I/susenergy2030.html.
45. Dvorak, M., C.L. Archer, and M.Z. Jacobson, California offshore wind energy potential, *Renewable Energy*, 35, 1244-1254, doi:10.1016/j.renene.2009.11.022, 2010, http://www.stanford.edu/group/efmh/jacobson/Articles/I/Offshore/offshore.html.
46. Dvorak, M.J., B.A. Corcoran, J.E. Ten Hoeve, N.G. McIntyre, and M.Z. Jacobson, U.S. East Coast offshore wind energy resources and their relationship to peak-time electricity demand, *Wind Energy*, 16, 977-997, doi:10.1002/we.1524, 2012, http://www.stanford.edu/group/efmh/jacobson/Articles/I/Offshore/offshore.html.
47. Dvorak, M.J., E.D. Stoutenburg, C.L. Archer, W. Kempton, and M.Z. Jacobson, Where is the ideal location for a U.S. East Coast offshore grid, *Geophys. Res. Lett*., *39*, L06804, doi:10.1029/2011GL050659, 2012, http://www.stanford.edu/group/efmh/jacobson/Articles/I/Offshore/offshore.html.
48. Edgerton, S.A, M.C. MacCracken, M.Z. Jacobson, A. Ayala, C.E. Whitman, and M.C. Trexler, Critical review discussion: Prospects for future climate change and the reasons for early action, *Journal of the Air & Waste Management Association*, *58*, 1386-1400, 2008, http://web.stanford.edu/group/efmh/jacobson/Articles/Others/10.3155-1047-3289.58.11.1386.pdf.
49. Frew, B.A., S. Becker, M.J. Dvorak, G.B. Andresen, and M.Z. Jacobson, Flexibility mechanisms and pathways to a highly renewable U.S. electricity future, *Energy*, *101*, 65-78, 2016, http://www.stanford.edu/group/efmh/jacobson/Articles/Others/16-Frew-Energy.pdf.
50. Frew, B.A., and M.Z. Jacobson, Temporal and spatial tradeoffs in power system modeling with assumptions about storage: An application of the POWER model, *Energy*, 117, 198-213, 2016, http://www.stanford.edu/group/efmh/jacobson/Articles/Others/16-Frew-Energy-B.pdf.
51. Ginnebaugh, D.L., J. Liang, and M.Z. Jacobson, Examining the temperature dependence of ethanol (E85) versus gasoline emissions on air pollution with a largely-explicit chemical mechanism, *Atmos. Environ.*, *44*, 1192-1199, doi:10.1016/j.atmosenv.2009.12.024, 2010, www.stanford.edu/group/efmh/jacobson/Articles/I/E85vWindSol.

52. Ginnebaugh, D.L., and M.Z. Jacobson, Coupling of highly explicit gas and aqueous chemistry mechanisms for use in 3-D, *Atmos. Environ.*, *62*, 408-415 2012, www.stanford.edu/group/efmh/jacobson/Articles/I/E85vWindSol.
53. Ginnebaugh, D.L., and M.Z. Jacobson, Examining the impacts of ethanol (E85) versus gasoline photochemical production of smog in a fog using near-explicit gas- and aqueous-chemistry mechanisms, *Environmental Research Letters*, 7, 045901, doi:10.1088/1748-9326/7/4/045901, 2012, www.stanford.edu/group/efmh/jacobson/Articles/I/E85vWindSol.
54. Hart, E.K., and M.Z. Jacobson, A Monte Carlo approach to generator portfolio planning and carbon emissions assessments of systems with large penetrations of variable renewables, *Renewable Energy*, *36*, 2278-2286, doi:10.1016/j.renene.2011.01.015, 2011, www.stanford.edu/group/efmh/jacobson/Articles/I/CombiningRenew/combining.html.
55. Hart, E.K., E.D. Stoutenburg, and M.Z. Jacobson, The potential of intermittent renewables to meet electric power demand: A review of current analytical techniques, *Proceedings of the IEEE*, *100*, 322-334, doi:10.1109/JPROC.2011.2144951, 2012, www.stanford.edu/group/efmh/jacobson/Articles/I/CombiningRenew/combining.html.
56. Hart, E.K., and M.Z. Jacobson, The carbon abatement potential of high penetration intermittent renewables, *Energy and Environmental Science*, *5*, 6592-6601, doi:10.1039/C2EE03490E, 2012, www.stanford.edu/group/efmh/jacobson/Articles/I/CombiningRenew/combining.html.
57. Hou, P., P. Enevoldsen, J. Eichman, W. Hu, M.Z. Jacobson, and Z. Chen, Optimizing investments in coupled offshore wind-electrolytic hydrogen storage systems in Denmark, J. Power Sources, 359, 186-197, 2017, doi:10.1016/j.jpowsour.2017.05.048.
58. Hu, X.-M, Y. Zhang, M.Z. Jacobson, and C.K. Chan, Coupling and evaluating gas/particle mass transfer treatments for aerosol simulation and forecast, *J. Geophys. Res*., 113, D11208, doi:10.1029/2007JD009588, 2008, http://web.stanford.edu/group/efmh/jacobson/Articles/Others/2007JD009588.pdf.
59. Jiang, Q., J.D. Doyle, T. Haack, M.J. Dvorak, *C.L. Archer*, and M.Z. Jacobson, Exploring wind energy potential off the California coast, *Geophys. Res. Lett*., 35, L20819, doi:10.1029/2008GL034674, 2008, http://web.stanford.edu/group/efmh/jacobson/Articles/Others/2008GL034674.pdf.
60. Kempton, W., C.L. Archer, A. Dhanju, R.W. Garvine, and M.Z. Jacobson, Large CO_2 reductions via offshore wind power matched to inherent storage in energy end-uses, *Geophys. Res. Lett*., 34, L02817, doi:10.1029/2006GL028016, 2007, http://web.stanford.edu/group/efmh/jacobson/Articles/Others/2006GL028016.pdf.
61. Ketefian, G.S., and M.Z. Jacobson, A mass, energy, vorticity, and potential enstrophy conserving lateral fluid-land boundary scheme for the shallow water equations, *J. Comp. Phys*., *228*, 1-32, doi:10.1016/j.jcp.2008.08.009, 2009, http://www.stanford.edu/~gsk/Ketefian_Jacobson_2009.pdf.
62. *Ketefian, G.S.*, and M.Z. Jacobson, A mass, energy, vorticity, and potential enstrophy conserving lateral boundary scheme for the shallow water equations using piecewise linear boundary approximations, *J. Comp. Phys*., *230*, 2751-2793, doi:10.1016/j.jcp2010.11.008, 2011, http://www.stanford.edu/~gsk/.
63. *Liang, J.*, and M.Z. Jacobson, CVPS: An operator solving complex chemical and vertical processes simultaneously with sparse-matrix techniques, *Atmos. Environ*., *45*, 6820-6827, doi:10.1016/j.atmosenv.2010.12.035, 2011, http://web.stanford.edu/group/efmh/jacobson/Articles/Others/OpSparsMat2011.pdf.
64. Morrison, G.M., S.Yeh, A.R. Eggert, C. Yang, J.H. Nelson, Alphabetic: J.B. Greenblatt, R. Isaac, M.Z. Jacobson, J Johnston, D.M. Kammen, A. Mileva, J. Moore, D. Roland-Holst, M. Wei, J.P. Weyant, J.H. Williams, R. Williams, C.B. Zapata, Comparison of low-carbon pathways for California, *Climatic Change*, *131*, 540-557, doi:10.1007/s10584-015-1403-5, 2015, http://web.stanford.edu/group/efmh/jacobson/Articles/Others/15-04-ClimaticChangeLowCarb.pdf.
65. Naiman, A.D., S.K. Lele, J.T. Wilkerson, and M.Z. Jacobson, Parameterization of subgrid plume dilution for use in large-scale atmospheric simulations, *Atmos. Chem. Phys*., 10, 2551-2560, 2010, www.stanford.edu/group/efmh/jacobson/Articles/VIII/aircraftflights.html.
66. Naiman, A.D., S.K. Lele, and M.Z. Jacobson, Large eddy simulations of contrail development: Sensitivity to initial and ambient conditions over first twenty minutes, *J. Geophys. Res*., *116*, D21208, doi:10.1029/2011JD015806, 2011, www.stanford.edu/group/efmh/jacobson/Articles/VIII/aircraftflights.html.
67. Olsen, S.C., G.P. Brasseur, D.J. Wuebbles, S.R.H. Barrett, H. Dang, S.D. Eastham, M.Z. Jacobson, A. Khodayari, H. Selkirk, A. Sokolov, N. Unger, Comparison of model estimates of the effects of aviation emissions on atmospheric ozone and methane, *Geophys. Res. Lett*., *40*, 6004-6009, 2013, http://web.stanford.edu/group/efmh/jacobson/Articles/Others/13OlsenGRL.pdf.

68. Sta. Maria, M.R.V., and M.Z. Jacobson, Investigating the effect of large wind farms on energy in the atmosphere, *Energies*, 2, 816-836, doi:10.3390/en20400816, 2009, www.stanford.edu/group/efmh/jacobson/Articles/I/windfarms.html.
69. Stoutenburg, E.D., N. Jenkins, and M.Z. Jacobson, Power output variations of co-located offshore wind turbines and wave energy converters in California, *Renewable Energy*, *35*, 2781-2791, doi:10.1016/j.renene.2010.04.033, 2010, www.stanford.edu/group/efmh/jacobson/Articles/I/Wind&wave/wind&wave.html.
70. Stoutenburg, E.K., and M.Z. Jacobson, Reducing offshore transmission requirements by combining offshore wind and wave farms, *IEEE Journal of Oceanic Engineering*, *36*, 552-561, doi:10.1109/JOE.2011.2167198, 2011, www.stanford.edu/group/efmh/jacobson/Articles/I/Wind&wave/wind&wave.html.
71. Stoutenburg, E.D., N. Jenkins, and M.Z. Jacobson, Variability and uncertainty of wind power in the California electric power system, *Wind Energy*, *17*, 1411-1424, doi:10.1002/we.1640, 2014, http://web.stanford.edu/group/efmh/jacobson/Articles/I/CombiningRenew/EStoutWindEn13.pdf
72. Ten Hoeve, J.E, L.A. Remer, and M.Z. Jacobson, Microphysical and radiative effects of aerosols on warm clouds during the Amazon biomass burning season as observed by MODIS: impacts of water vapor and land cover, *Atmos. Chem. Phys. 11*, 3021-3036, 2011, www.stanford.edu/group/efmh/jacobson/Articles/VII/CloudAbsorption.html.
73. Ten Hoeve, J.E., M.Z. Jacobson, and L. Remer, Comparing results from a physical model with satellite and in situ observations to determine whether biomass burning aerosols over the Amazon brighten or burn off clouds, *J. Geophys. Res*., *117*, D08203, doi:10.1029/2011JD016856, 2012, www.stanford.edu/group/efmh/jacobson/Articles/VII/CloudAbsorption.html.
74. Ten Hoeve, J.E., L.A. Remer, A.L. Correia, and M.Z. Jacobson, Recent shift from forest to savanna burning in the Amazon basin observed from satellite, *Environmental Research Letters*, *7*, 024020, doi:10.1088/1748-9326/7/2/024020, 2012, http://www.stanford.edu/group/efmh/jacobson/Articles/VIII/bioburn/index.html.
75. Ten Hoeve, J.E., and M.Z. Jacobson, Worldwide health effects of the Fukushima Daiichi nuclear accident, *Energy and Environmental Sciences*, *5*, 8743-8757, doi:10.1039/c2ee22019a, 2012, http://www.stanford.edu/group/efmh/jacobson/fukushima.html.
76. Whitt, D.B., J.T. Wilkerson, M.Z. Jacobson, A.D. Naiman, and S.K. Lele, Vertical mixing of commercial aviation emissions from cruise altitude to the surface, *Journal of Geophysical Research*., *116*, D14109, doi:1029/2010JD015532, 2011, www.stanford.edu/group/efmh/jacobson/Articles/VIII/aircraftflights.html.
77. Wilkerson, J.T., M.Z. Jacobson, A. Malwitz, S. Balasubramanian, R. Wayson, G. Fleming, A.D. Naiman, and S.K. Lele, Analysis of emission data from global commercial aviation: 2004 and 2006, *Atmos. Chem. Phys.*, *10*, 6391-6408, 2010, www.stanford.edu/group/efmh/jacobson/Articles/VIII/aircraftflights.html.
78. Zamora, I.R., A. Tabazadeh, D.M. Golden, and M.Z. Jacobson, Hygroscopic growth of common organic aerosol solutes, including humic substances, as derived from water activity measurements, *J. Geophys. Res*., *116*, D23207, doi:10.1029/2011JD016067, 2011, http://www.stanford.edu/group/efmh/jacobson/Articles/Others/ZamoraJGR11.pdf.
79. Zamora, I.R., and M.Z. Jacobson, Measuring and modeling the hygroscopic growth of two humic substances in mixed aerosol particles of atmospheric relevance, *Atmos. Chem. Phys.*, *13*, 8973-8989, doi:10.5194/acp-13-8973-2013, 2013, http://www.atmos-chem-phys.net/13/8973/2013/.
80. Zhang, Y., K. Vijayaraghavan, X. Wen, H.E. Snell, and M.Z. Jacobson, Probing into regional ozone and particulate matter pollution in the United States: Part I. A 1-year CMAQ simulation and evaluation using surface and satellite data, *J. Geophys. Res*., 114, D22304, doi:10.1029/2009JD011898, 2009, http://web.stanford.edu/group/efmh/jacobson/Articles/Others/2009JD011898.pdf.
81. Zhang, Y., X. Wen, K. Wang, K. Vijayaraghavan, and M.Z. Jacobson, Probing into regional O_3 and particulate matter pollution in the United States: 2. An examination of formation mechanisms through a process analysis technique and sensitivity study, *J. Geophys. Res*., 114, D22305, doi:1029/2009JD011900, 2009, http://web.stanford.edu/group/efmh/jacobson/Articles/Others/2009JD011900.pdf.
82. Zhang, Y., P. Liu, X.-H. Liu, B. Pun, C. Seigneur, M.Z. Jacobson, W. Wang, Fine scale modeling of wintertime aerosol mass, number, and size distributions in Central California, *J. Geophys. Res*., *115*, D15207, doi:10.1029/2009JD012950, 2010, http://web.stanford.edu/group/efmh/jacobson/Articles/Others/2009JD012950.pdf.
83. Zhang, Y., P. Liu, X.-H. Liu, M.Z. Jacobson, P.H. McMurry, F. Yu, S. Yu, and K.L. Schere, A comparative study of homogeneous nucleation parameterizations: 2. Three-dimensional model application and evaluation, *J. Geophys. Res*., *115*, D20213, doi:10.1029/2010JD014151, 2010, http://web.stanford.edu/group/efmh/jacobson/Articles/Others/2010JD014151.pdf.

84. Zhang, Y., P.H. McMurry, F. Yu, and M.Z. Jacobson, A comparative study of nucleation parameterizations: 1. Examination and evaluation of the formulations, *J. Geophys. Res.*, *115*, D20212, doi:10.1029/2010JD014150, 2010, http://web.stanford.edu/group/efmh/jacobson/Articles/Others/2010JD014150.pdf.

Textbooks

Jacobson, M.Z., *Fundamentals of Atmospheric Modeling,* Cambridge University Press, New York, 656 pp., 1999; reprint, 2000.

Jacobson, M.Z., *Fundamentals of Atmospheric Modeling, Second Edition*, Cambridge University Press, New York, 813 pp., 2005.

Jacobson, M. Z., *Atmospheric Pollution: History, Science, and Regulation*, Cambridge University Press, New York, 399 pp., 2002.

Jacobson, M. Z., *Air Pollution and Global Warming: History, Science, and Solutions*, Cambridge University Press, New York, in press, 2012.

Invited Congressional Testimony

July 12, 2005. Written testimony on a comparison of wind with nuclear energy to the U.S. House of Representatives Subcommittee on Energy and Resource, and accepted into the Congressional Record (testimony requested by Dr. Rowan Rowntree).

October 18, 2007. Oral and written testimony on the role of black carbon as a factor in climate change and its impact on public health. U.S. House of Representatives Committee on Oversight and Government Reform, Washington, D.C. http://www.stanford.edu/group/efmh/jacobson/101807_testimony.htm.

April 9, 2008. Oral and written testimony on the relative impact of carbon dioxide on air pollution health problems in California versus the rest of the U.S., U.S. House of Representatives Select Committee on Energy Independence and Global Warming, Washington, D.C. http://www.stanford.edu/group/efmh/jacobson/040908_testimony.htm.

November 19, 2015, Oral and written testimony on powering the 50 United States and 139 countries with 100% wind, water, and solar power for all purposes, U.S. House of Representatives, Energy and Commerce Committee, Washington, D.C., https://democrats-energycommerce.house.gov/committee-activity/hearings/democratic-forum-on-global-solutions-to-climate-change-full-committee, Written testimony: http://web.stanford.edu/group/efmh/jacobson/Articles/I/15-11-19-HouseEEC-MZJTestimony.pdf

Invited EPA Testimony

Oral testimony invited by the State of California at the Environmental Protection Agency Hearing AMS-FRL-8772-7, California State Motor Vehicle Control Standards; Greenhouse Gas Regulations; Reconsideration of Previous Denial of a Waiver of Preemption, Arlington, Virginia March 5, 2009. http://www.stanford.edu/group/efmh/jacobson/EPAhearing.html.

Oral testimony at the Environmental Protection Agency Hearing: Endangerment and cause or contribute findings for greenhouse gases under the Clean Air Act, Arlington, Virginia, May 18, 2009. http://www.stanford.edu/group/efmh/jacobson/greenhousegases.html.

Utility Board Testimony

June 17, 2016, Written testimony to the Iowa Utilities Board on the feasibility of Iowa, Roadmap to transition Iowa to 100% wind, water, and solar (WWS) power for all purposes by 2050, with 80% conversion by 2030.

Invited Court Briefs

Brief of *amici curiae* climate scientists James Hansen, Mark Z. Jacobson, Michael Kleeman, Benjamin Santer, and Stephen H. Schneider in Support of the State of California in State of California v. U.S. Environmental Protection, U.S. Court of Appeals for the Ninth Circuit (No. 08-70011), June, 2008.

Motion for leave to file brief of proposed amica curiae climate scientists Inez Fung, James Hansen, Mark Z. Jacobson, Michael Kleeman, Benjamin Santer, Stephen H. Schneider, and James C. Zachos in support of respondents, Chamber of Commerce of the United States of America et al. vs. United States Environmental Protection Agency (No. 09-1237), November, 2009.

Brief for Respondents United States Environmental Protection Agency, et al., in Chamber of Commerce of the United States of America, et al., v. United States Environmental Protection Agency, et al., in the United States Court of Appeals for the District of Columbia Circuit, No. 09-1237, Filed August 26, 2010.

Brief of *amici curiae* atmospheric scientists and air quality modeling experts William Chameides, Arlene Fiore, Tracey Holloway, Mark Jacobson, Paul Miller, and Mehmet Odman in support of Petitioners, U.S. Environmental Protection Agency et al. and American Lung Association et al. v. EME Homer City Generation L.P., et al. (No. 12-1182, -1183) in the Supreme Court of the United States of America, September 11, 2013, http://law.wustl.edu/news/pages.aspx?id=10120.

Brief of *amici curiae* in support of respondents and cross-appellants; Proposed brief of *amici curiae* climate scientists Dennis D. Baldocchi, Ph.D., Robert A. Eagle, Ph.D., Marc Fischer, Ph.D., John Harte, Ph.D., Mark Z. Jacobson, Ph.D., Ralph Keeling, Ph.D., James C. Williams, Ph.D., Terry L. Root, Ph.D., Richard C.J. Somerville, Ph.D., Aradhna K. Tripati, Ph.D., and Anthony L. Westerling, Ph.D., Cleveland National Forest Foundation; Sierra Club; Center for Biological Diversity; Creed-21; Affordable Housing Coalition of San Diego County; People of the State of California Respondents and Cross-Appellants, v. San Diego Association of Governments; San Diego Association of Governments Board of Directors, Appellants and Cross-Respondents. Court of Appeal of the State of California, Fourth Appellate District, Division One.

Declaration of Mark Z. Jacobson, PhD, in support of Western Environmental Law Center and Our Children's Trust's Comments on Proposed Clean Air Rule, Submitted to the Washington Department of Ecology, July 21, 2016.

EXHIBIT B: REFERENCES

Allred, B.W., W.K. Smith, D. Twidwell, J.H. Haggerty, S.W. Running, D.E. Naugle, and S.D. Fuhlendorf, 2015. Ecosystem services lost to oil and gas in North America, *Science*, 348, 401-402.

Boden, T., B. Andres, and G. Marland, 2011. Global CO_2 emissions from fossil-fuel burning, cement manufacture, and gas flaring, 1751-2011, http://cdiac.ornl.gov/ftp/ndp030/global.1751_2011.ems, Accessed Nov. 27, 2015.

Cooper, M., 2016. The economic and institutional foundations of the Paris Agreement on climate change: The political economy of roadmaps to a sustainable electricity future. http://dx.doi.org/10.2139/ssrn.2722880, Accessed May 12, 2017.

U.S. Energy Information Agency (EIA), 2017. Analysis & Projections, Table A19, Energy-related carbon dioxide emissions by end-use (2015-2050) (Reference Case and Reference Case with Clean Power Plan), https://www.eia.gov/analysis/projection-data.cfm#annualproj, Accessed July 25, 2017.

U.S. Energy Information Agency (EIA), 2017. Carbon Dioxide Emissions from Energy Consumption (1973-2015) by Source, www.eia.gov/totalenergy/data/browser/, published April, 25, 2017, Accessed July 25, 2017.

Seidel, S., D. Keyes (EPA), 1983. Can We Delay a Greenhouse Warming? Environmental Protection Agency, Strategic Studies Staff Office of Policy Analysis, Office of Policy and Resources Management.

Lashof, D.A., D.A. Tirpak (EPA), 1990. Policy Options for Stabilizing Global Climate: Report to Congress, United States Environmental Protection Agency, Office of Policy, Planning and Evaluation.

Fracktracker Alliance, 2015, https://www.fractracker.org/2015/08/1-7-million-wells/, Accessed June 5, 2017.

Freed J., Allen T. Nordhaus T., Lovering J., 2017. Is nuclear too innovative? Third Way, https://medium.com/third-way/is-nuclear-too-innovative-a14fb4fef41a#.qag59xnk0, Accessed Feb. 28, 2017.

Friedlingstein P. et al., 2014. Persistent growth of CO_2 emissions and implications for reaching climate targets, *Nature Geoscience* 7: 709–715.

Houghton, R. A., J.I. House, J. Pongratz, G.R. van der Werf, R.S. DeFries, M.C. Hansen, C. Le Quéré, and N. Ramankutty, 2012. Carbon emissions from land use and land-cover change, *Biogeosciences* 9: 5125–5142, doi:10.5194/bg-9-5125-2012.

IPCC (Intergovernmental Panel on Climate Change), 2000. Special Report on Emission Scenarios (SRES), http://sres.ciesin.org/final_data.html, Accessed November 19, 2015.

IPCC (Intergovernmental Panel on Climate Change) full citation: Bruckner T., I.A. Bashmakov, Y. Mulugetta, H. Chum, A. de la Vega Navarro, J. Edmonds, A. Faaij, B. Fungtammasan, A. Garg, E. Hertwich, D. Honnery, D. Infield, M. Kainuma, S. Khennas, S. Kim, H.B. Nimir, K. Riahi, N. Strachan, R. Wiser, and X. Zhang (2014): Energy Systems. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth*

Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jacobson, M.Z., 2005. Studying ocean acidification with conservative, stable numerical schemes for nonequilibrium air-ocean exchange and ocean equilibrium chemistry, *J. Geophys. Res.* 110, D07302, doi:10.1029/2004JD005220.

Jacobson, M.Z., 2007. Effects of ethanol (E85) versus gasoline vehicles on cancer and mortality in the United States, *Environ. Sci. Technol.* 41 (11): 4150-4157, doi:10.1021/es062085v.

Jacobson M.Z., 2009. Review of solutions to global warming, air pollution, and energy security. *Energy & Environmental Science* 2: 148-173.

Jacobson, M.Z., M.A. Delucchi, G. Bazouin, Z.A.F. Bauer, C.C. Heavey, E. Fisher, S. B. Morris, D.J.Y. Piekutowski, T.A. Vencill, and T.W. Yeskoo, 2015a. 100% clean and renewable wind, water, and sunlight (WWS) all-sector energy roadmaps for the 50 United States. *Energy Environ Sci.* 8: 2093-2117.
Paper: http://web.stanford.edu/group/efmh/jacobson/Articles/I/USStatesWWS.pdf
Spreadsheet: https://web.stanford.edu/group/efmh/jacobson/Articles/I/USStates.xlsx

Jacobson, M.Z., M.A. Delucchi, M.A. Cameron, and B.A. Frew, 2015b. A low-cost solution to the grid reliability problem with 100% penetration of intermittent wind, water, and solar for all purposes. *Proc. Natl. Acad. Sci.* 112: 15,060-15,065.
Paper:http://web.stanford.edu/group/efmh/jacobson/Articles/I/CombiningRenew/CONUSGridIntegration.pdf
Clarification:http://web.stanford.edu/group/efmh/jacobson/Articles/I/CombiningRenew/Clarification-PNAS15.pdf

Jacobson, M.Z., M.A. Delucchi, M.A. Cameron, and B.A. Frew, Reply to Bistline and Blanford: Letter reaffirms conclusions and highlights flaws in previous research, *Proc. National Acad. Sci*, 113, E3989-E3990, doi:pnas.1606802113, 2016.
Paper:http://web.stanford.edu/group/efmh/jacobson/Articles/I/CombiningRenew/PNASReplyLetter.pdf

Jacobson, M.Z., M.A. Delucchi, Z.A.F. Bauer, S.C. Goodman, W.E. Chapman, M.A. Cameron, Alphabetical: C. Bozonnat, L. Chobadi, H.A. Clonts, P. Enevoldsen, J.R. Erwin, S.N. Fobi, O.K. Goldstrom, E.M. Hennessy, J. Liu, J. Lo, C.B. Meyer, S.B. Morris, K.R. Moy, P.L. O'Neill, I. Petkov, S. Redfern, R. Schucker, M.A. Sontag, J. Wang, E. Weiner, A.S. Yachanin, 2017a. 100% clean and renewable wind, water, and sunlight (WWS) all-sector energy roadmaps for 139 countries of the world, *Joule, 1*, 108-121,
Paper: http://web.stanford.edu/group/efmh/jacobson/Articles/I/CountriesWWS.pdf
Spreadsheet: https://web.stanford.edu/group/efmh/jacobson/Articles/I/AllCountries.xlsx

Jacobson, M.Z., M.A. Delucchi, M.A. Cameron, and B.A. Frew, 2017b. The United States can keep the grid stable at low cost with 100% clean, renewable energy in all sectors despite inaccurate claims, *Proc. National Acad. Sci., 114*, ES021-ES023, doi:10.1073/pnas.1708069114.
Paper:http://web.stanford.edu/group/efmh/jacobson/Articles/I/CombiningRenew/PNASReplyClack.pdf.

Jacobson, M.Z., M.A. Delucchi, M.A. Cameron, and B.V, Mathiesen, 2018. Matching demand with supply at low cost among 139 countries within 20 world regions with 100% intermittent wind, water, and sunlight (WWS) for all purposes, *Renewable Energy*, 123, 236-248 Paper:https://web.stanford.edu/group/efmh/jacobson/Articles/I/CombiningRenew/WorldGridIntegration.pdf

Lazard, 2017. *Lazard's levelized cost of energy analysis – Version 11.0*, https://www.lazard.com/perspective/levelized-cost-of-energy-2017/, Accessed April 3, 2018.

Le Quere, C. et al., 2015, Global carbon budget 2014, *Earth Syst. Sci. Data* 7: 47-85, https://www.earth-syst-sci-data.net/7/47/2015/essd-7-47-2015.pdf.

Matthews, H.D., 2016. Montreal's emissions targets for 1.5 ^{o}C and 2^{o}C global warming, http://ocpm.qc.ca/sites/ocpm.qc.ca/files/pdf/P80/7.2.19_damon_matthews.pdf, Accessed Sept. 22, 2016.

Meko, T. and L. Karklis, 2017. The United States of Oil and Gas, Wash. Post, Feb. 14 2017, https://www.washingtonpost.com/graphics/national/united-states-of-oil/, Accessed July 24, 2017.

Neftel, A., H. Friedli, E. Moor, H. Lotscher, H. Oeschger, U. Siegenthaler, and B. Stauffer, 1994. Historical CO_2 record from the Siple station ice core, http://cdiac.ornl.gov/ftp/trends/co2/siple2.013, Accessed Nov. 27, 2015.

U.S. Congress, Office of Technology Assessment (OTA), 1991. Changing by Degrees: Steps to Reduce Greenhouse Gases, OTA-O-482, Washington, DC: U.S. Government Printing Office.

Pennsylvania Department of Environmental Protection, 2016. 2016 oil and gas annual report, http://www.depgis.state.pa.us/oilgasannualreport/index.html, Accessed June 5, 2017.

Schlesinger, J., 1978. Domestic Policy Review of Solar Energy: A Response Memorandum to the President of the United States.

Tans, P. and R.F. Keeling, 2015. Trends in atmospheric carbon dioxide, http://www.esrl.noaa.gov/gmd/ccgg/trends/#mlo_full, Accessed Nov. 27, 2015.

UNFCCC, A Summary of Kyoto Protocol, http://unfccc.int/kyoto_protocol/background/items/2879.php, Accessed July 25, 2017.

U.S. White House, 2016. U.S. Mid Century Strategy for Deep Decarbonization.

EXHIBIT C: PREVIOUS TESTIMONY

Invited Congressional Testimony

July 12, 2005. Written testimony on a comparison of wind with nuclear energy to the U.S. House of Representatives Subcommittee on Energy and Resource, and accepted into the Congressional Record (testimony requested by Dr. Rowan Rowntree).

October 18, 2007. Oral and written testimony on the role of black carbon as a factor in climate change and its impact on public health. U.S. House of Representatives Committee on Oversight and Government Reform, Washington, D.C. http://www.stanford.edu/group/efmh/jacobson/101807_testimony.htm.

April 9, 2008. Oral and written testimony on the relative impact of carbon dioxide on air pollution health problems in California versus the rest of the U.S., U.S. House of Representatives Select Committee on Energy Independence and Global Warming, Washington, D.C. http://www.stanford.edu/group/efmh/jacobson/040908_testimony.htm.

November 19, 2015, Oral and written testimony on powering the 50 United States and 139 countries with 100% wind, water, and solar power for all purposes, U.S. House of Representatives, Energy and Commerce Committee, Washington, D.C., https://democrats-energycommerce.house.gov/committee-activity/hearings/democratic-forum-on-global-solutions-to-climate-change-full-committee, Written testimony: http://web.stanford.edu/group/efmh/jacobson/Articles/I/15-11-19-HouseEEC-MZJTestimony.pdf

Invited EPA Testimony

Oral testimony invited by the State of California at the Environmental Protection Agency Hearing AMS-FRL-8772-7, California State Motor Vehicle Control Standards; Greenhouse Gas Regulations; Reconsideration of Previous Denial of a Waiver of Preemption, Arlington, Virginia March 5, 2009. http://www.stanford.edu/group/efmh/jacobson/EPAhearing.html.

Oral testimony at the Environmental Protection Agency Hearing: Endangerment and cause or contribute findings for greenhouse gases under the Clean Air Act, Arlington, Virginia, May 18, 2009. http://www.stanford.edu/group/efmh/jacobson/greenhousegases.html.

Utility Board Testimony

June 17, 2016, Written testimony to the Iowa Utilities Board on the feasibility of Iowa, Roadmap to transition Iowa to 100% wind, water, and solar (WWS) power for all purposes by 2050, with 80% conversion by 2030.

Invited Court Briefs

Brief of *amici curiae* climate scientists James Hansen, Mark Z. Jacobson, Michael Kleeman, Benjamin Santer, and Stephen H. Schneider in Support of the State of California in State of California v. U.S. Environmental Protection, U.S. Court of Appeals for the Ninth Circuit (No. 08-70011), June, 2008.

Motion for leave to file brief of proposed amicus curiae climate scientists Inez Fung, James Hansen, Mark Z. Jacobson, Michael Kleeman, Benjamin Santer, Stephen H. Schneider, and James C. Zachos in support of respondents, Chamber of Commerce of the United States of America et al. vs. United States Environmental Protection Agency (No. 09-1237), November, 2009.

Brief for Respondents United States Environmental Protection Agency, et al., in Chamber of Commerce of the United States of America, et al., v. United States Environmental Protection Agency, et al., in the United States Court of Appeals for the District of Columbia Circuit, No. 09-1237, Filed August 26, 2010.

Brief of *amici curiae* atmospheric scientists and air quality modeling experts William Chameides, Arlene Fiore, Tracey Holloway, Mark Jacobson, Paul Miller, and Mehmet Odman in support of Petitioners, U.S. Environmental Protection Agency et al. and American Lung Association et al. v. EME Homer City Generation L.P., et al. (No. 12-1182, -1183) in the Supreme Court of the United States of America, September 11, 2013, http://law.wustl.edu/news/pages.aspx?id=10120.

Brief of *amici curiae* in support of respondents and cross-appellants; Proposed brief of *amici curiae* climate scientists Dennis D. Baldocchi, Ph.D., Robert A. Eagle, Ph.D., Marc Fischer, Ph.D., John Harte, Ph.D., Mark Z. Jacobson, Ph.D., Ralph Keeling, Ph.D., James C. Williams, Ph.D., Terry L. Root, Ph.D., Richard C.J. Somerville, Ph.D., Aradhna K. Tripati, Ph.D., and Anthony L. Westerling, Ph.D., Cleveland National Forest Foundation; Sierra Club; Center for Biological Diversity; Creed-21; Affordable Housing Coalition of San Diego County; People of the State of California Respondents and Cross-Appellants, v. San Diego Association of Governments; San Diego Association of Governments Board of Directors, Appellants and Cross-Respondents. Court of Appeal of the State of California, Fourth Appellate District, Division One.

Declaration of Mark Z. Jacobson, PhD, in support of Western Environmental Law Center and Our Children's Trust's Comments on Proposed Clean Air Rule, Submitted to the Washington Department of Ecology, July 21, 2016.

EXHIBIT D: DECARBONIZATION STUDIES

Publication	Sector(s)	Change Modeled
Mason, I.G., SC Page, and AG. Williamson, 2010. A 100% renewable electricity generation system for New Zealand utilizing hydro, wind, geothermal and biomass, *Energy Policy* 38 (8): 3973-3984, doi.org/10.1016/j.enpol.2010.03.022.	Electricity	100% renewable electricity in New Zealand
Connolly, D. and BV. Mathiesen, 2014. A technical and economic analysis of one potential pathway to a 100% renewable energy system, *International Journal of Sustainable Energy Planning and Management* 1, doi.org/10.5278/ijsepm.2014.1.2.	Electricity, heating/cooling, transportation	100% renewable Ireland by 2050
Connolly, D., H. Lund, and BV. Mathiesen, 2016. Smart energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union, *Renewable and Sustainable Energy Reviews* 60: 1634–1653, doi.org/10.1016/j.rser.2016.02.025.	Electricity, heating/cooling, transportation	100% renewable for all uses in Europe by 2050
Mathiesen, BV., H. Lund, and K. Karlsson, 2011. 100% Renewable energy systems, climate mitigation and economic growth, *Applied Energy* 88 (2): 488-501, doi.org/10.1016/j.apenergy.2010.03.001.	Electricity, heating/cooling, transportation	100% renewable for all uses by 2050
Mathiesen, BV., et al., 2015. Energy systems for coherent 100% renewable energy and transport solutions, *Applied Energy* 145: 139-154, doi.org/10.1016/j.apenergy.2015.01.075.	Electricity, heating/cooling, transportation	100% renewable for all uses
Elliston, B., I. MacGill, and M. Diesendorf, 2013. Least cost 100% renewable electricity scenarios in the Australian National Electricity Market, *Energy Policy* 59: 270-282, doi.org/10.1016/j.enpol.2013.03.038.	Electricity	100% renewable electricity
Elliston, B., I. MacGill, and M. Diesendorf, 2014. Comparing least cost scenarios for 100% renewable electricity with low emission fossil fuel scenarios in the Australian National Electricity Market, *Renewable Energy* 66: 196-204, doi.org/10.1016/j.renene.2013.12.010.	Electricity	100% renewable energy for electricity
Budischak, C., et al., 2013. Cost-minimized combinations of wind power, solar power and electrochemical storage, powering the grid up to 99.9% of the time. *Journal of Power Sources* 225: 60-74, doi.org/10.1016/j.jpowsour.2012.09.054.	Electricity	90-99.9% renewable electricity in US territory covered by PJM
MacDonald, A.E., C.T. Clack, et.al., 2016. Future cost-competitive electricity systems and their impact on US CO_2 emissions, *Nature Climate Change* 6: 526–531, doi:10.1038/nclimate2921.	Electricity	GHGs 78% below 1990 levels by 2030

Williams, J.H., B. Haley, F. Kahrl, J. Moore, A.D. Jones, M.S. Torn, and H. McJeon, 2014. Pathways to deep decarbonization in the United States, *SDSN – IDDRI*, http://unsdsn.org/wp-content/uploads/2014/09/US-Deep-Decarbonization- Report.pdf.	All sectors	GHGs 80% below 1990 levels by 2050
United States White House, 2016. *U.S. Mid Century Strategy for Deep Decarbonization*, https://unfccc.int/files/focus/long-term_strategies/application/pdf/mid_century_strategy_report-final_red.pdf	All sectors	All greenhouse gas emissions 80%+ below 2005 by 2050.
Hand, M.M., S. Baldwin, E. DeMeo, J.M. Reilly, T. Mai, D. Arent, G. Porro, M. Meshek, and D. Sandor, eds. 4 vols., 2012. Renewable Electricity Futures Study (Entire Report) *National Renewable Energy Laboratory NREL*/TP-6A20-52409. Golden, CO: National Renewable Energy Laboratory, http://www.nrel.gov/analysis/re_futures/.	Electricity	Renewables could supply 80% of total U.S. electric generation by 2050
Mai, T., D. Mulcahy, MM Hand; and SF Baldwin, 2014. Envisioning a renewable electricity future for the United States, Energy 65: 374-386, doi.org/10.1016/j.energy.2013.11.029.	Electricity	80% renewable electricity by 2050
Arent, D., J. Pless, et.al., 2014. Implications of high renewable electricity penetration in the U.S. for water use, greenhouse gas emissions, land-use, and materials supply, Applied Energy 123: 368-377, doi.org/10.1016/j.apenergy.2015.01.075.	Electricity	80% renewable electricity by 2050
Mathiesen, B.V., H. Lund, et.al., 2015. Smart energy systems for coherent 100% renewable energy and transport solutions, *Applied Energy* 145: 139-154, doi.org/10.1016/j.apenergy.2015.01.075.	Electricity, heating, transportation	100% renewable Denmark by 2050
Connolly, D., BV Mathiesen, 2014. A technical and economic analysis of one potential pathway to a 100% renewable energy system, *International Journal of Sustainable Energy Planning and Management* 1, https://journals.aau.dk/index.php/sepm/article/view/497.	Electricity, heating/cooling, transportation	100% renewable Ireland by 2050
Bogdanov, D. and C. Breyer, 2016. North-East Asian Super Grid for 100% renewable energy supply: Optimal mix of energy technologies for electricity, gas and heat supply options, *Energy Conversion and Management* 112: 176-190, doi.org/10.1016/j.enconman.2016.01.019.	Electricity	100% renewable electricity in NE Asia by 2030
Parsons Brinkerhoff, 2009. Powering the Future: Mapping our Low-Carbon Path to 2050, http://hub.globalccsinstitute.com/sites/default/files/publications/138013/powering-future-mapping-low-carbon-path-2050.pdf.	All sectors of the UK economy	80% reduction in CO2 in the UK by 2050

Schellekens, G., A. Battaglini, J. Lilliestam, J. McDonnell, and A. Patt, 2010. 100% renewable electricity: A roadmap to 2050 for Europe and North Africa, *PricewaterhouseCoopers*, London, UK.	Electricity	100% renewable electricity in Europe and N. Africa by 2050
Wright, M. and P. Hearps, 2010. Zero Carbon Australia Stationary Energy Plan, *University of Melbourne Energy Research Institute*, http://media.bze.org.au/ZCA2020_Stationary_Energy_Report_v1.pdf.	Electricity, transportation, heating	100% renewable stationary power for Australia in 10 years.
Denis, A., Jotzo, F., et.al., 2014. Pathways to Deep Decarbonization in 2050: How Australia Can Prosper in a Low Carbon World, *SDSN – IDDRI*, http://deepdecarbonization.org/wp-content/uploads/2015/09/AU_DDPP_Report_Final.pdf.	Greenhouse gas emissions from all sources	Net zero emissions in Australia by 2050
McKinsey & Company, KEMA, The Energy Futures Lab at Imperial College London, Oxford Economics, and European Climate Foundation, 2010. Roadmap 2050: A Practical Guide to a Prosperous, Low Carbon Europe, Vol 1.: Technical Analysis, http://www.roadmap2050.eu/attachments/files/Volume1_fullreport_PressPack.pdf. E3G, The Energy Research Centre of the Netherlands, and European Climate Foundation, 2010. Roadmap 2050: A Practical Guide to a Prosperous, Low Carbon Europe, Vol 2.: Policy Recommendations, http://www.roadmap2050.eu/attachments/files/Volume2_Policy.pdf.	Greenhouse gas emissions from all sources	Reduce GHGs 80% below 1990 levels by 2050
Zervos, A., C. Lins, and J. Muth, 2010. Re-thinking 2050: A 100% Renewable Energy Vision for the European Union, *European Renewable Energy Council*, http://fft.szie.hu/mnt/Re-thinking%202050.pdf.	All sectors	100% renewable energy for the EU by 2050
Blake, L., P. Allen, et al., 2013. Zero Carbon Britain: Rethinking the future. *Center for Alternative Energy*, http://zerocarbonbritain.com/images/pdfs/ZCBrtflo-res.pdf.	All sectors	Net Zero GHG emissions in the UK by 2030
Bataille, C., et al., 2015. Pathways to deep decarbonization in Canada, *SDSN – IDDRI*, http://deepdecarbonization.org/wp-content/uploads/2015/09/DDPP_CAN.pdf.	All greenhouse gases, all sectors	90% below baseline scenario in 2050.
The négaWatt Association, 2017. The 2017-2050 négaWatt Scenario, *The négaWatt Association*, https://negawatt.org/IMG/pdf/negawatt-scenario-2017-2050_english-summary.pdf.	All sectors	100% renewable France by 2050

Aghahosseini, A., et al., 2018. Analysis of 100% renewable energy for Iran in 2030: Integrating solar PV, wind energy and storage, *International Journal of Environmental Science and Technology*,	Electricity	100% renewable Iran by 2030
Garcia-Olivares, A., et al., 2018. Transportation in a 100% renewable energy system, *Energy Conversion and Management*	Transportation	100% renewable global transportation.